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DESCRIPTIVE METEOROLOGY

DESCRIPTIVE METEOROLOGY

BY

WILLIS L. MOORE, LL.D., Sc.D.

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OF NATIONAL GEOGRAPHIC SOCIETY; VICE-PRESIDENT OF WASHINGTON ACADEMY
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FERREL, ABBE,
PIONEERS OF AMERICAN METEOROLOGY

PREFACE AND CREDITS

If this work is deemed to have merit it will be because for exactly a third of a century the author has had the privilege of access to what is probably the most complete meteorological library in the world, and of being a student of several of the able men who have constituted the scientific staff of the U. S. Weather Bureau, and because of his familiarity with the researches of Redfield, Espy, and Ferrel, and the works of Angot, Hann, Davis, and Waldo. He has consulted with and received valuable aid from Prof. Cleveland Abbe in the preparation of the matter on Precipitation, Clouds, and Colors of the Sky; Prof. Frank H. Bigelow on the Circulation of the Atmosphere; Prof. Herbert H. Kimball on Thermometry and on Winds; Prof. Alfred J. Henry and Librarian C. Fitzhugh Talman on Climate; Prof. Henry J. Cox on Frost; and Prof. W. J. Humphreys on many technical points in the physics of the book.

Special effort has been made to have the theory of meteorology lead up to the art of weather forecasting.

W. L. M.

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DESCRIPTIVE METEOROLOGY

INTRODUCTION

Scope of this Work.—Meteorology includes the whole range of the phenomena of the air: its composition, properties, motions, and the various forms of energy manifested therein. In this work its meaning will be given fully as broad a scope. We shall include the study of those known forms of energy that, through the medium of the ether or otherwise, reach the earth from the sun; and also of those portions of the hydrosphere and the lithosphere of the earth that have to do with the absorption, the radiation, the conduction, the reflection, and the distribution of heat; and its changes of form in the processes of evaporation, condensation, and freezing.

The Aim of the Author.—The object in writing this book was to provide, so far as possible, the young men entering the service of the U. S. Weather Bureau with a comprehensive introduction to modern meteorology. But to meet their needs in this particular is to provide equally well for all others who are beginning seriously this important science.

For several years the difficulty of directing the studies of these young men has been steadily increasing. Some of the better books on meteorology were fast becoming obsolete, as must always be the case with text-books that treat of a rapidly progressing science; while others, like Hann's masterly work, were, and still are, confined to the foreign languages in which they originally appeared. An urgent necessity, therefore, for a book that would bring the essentials of meteorology up to date, in an available form, was the incentive that led to the preparation of the present work.

The fact that meteorology may be an entirely new subject to the reader has constantly been kept in mind. Technical terms therefore have been defined wherever they first occur, and an effort has been made so to discuss the subjects under consideration as to leave the student with clear and correct ideas without the use of mathematics. This plan, it is believed, will render the book of the greatest help to the largest number.

Many new features have been introduced. Among them are:

(*a*) A graphical representation, based on the latest information, of the relative proportions, at various elevations, of all the important gases of the atmosphere.

(*b*) A discussion of the importance of dust particles in the air to the widely different phenomena of sky light, by which we get indirect illumination, and the condensation that precedes and leads to precipitation.

(*c*) A discussion, with the aid of an elaborate series of diagrams based on extensive cloud observations, of the movements of the air at various elevations in cyclones and anticyclones.

(*d*) A discussion, illustrated with diagrams, of the vertical distribution of temperature during different seasons and different weather conditions.

(*e*) An account, both descriptive and explanatory, of the isothermal layer, which, as sounding balloons have shown, is always and everywhere present.

(*f*) A chapter on weather forecasting, illustrated by over thirty typical charts of the weather. A study of this chapter should enable the layman, with the aid of a daily weather map, to make a good forecast of the coming weather for two or three days ahead.

Weather and Climate.—Many of the phenomena of which we shall treat may be broadly classified under the terms *Weather* and *Climate*. Weather expresses the conditions of the air at a definite time. One may properly speak of the weather of yesterday, but not of the climate, which is determined by taking the average of all the meteorological observations for a period of time great enough to eliminate the irregularities due to the variations of the weather from day to day. The science of weather, or *dynamic meteorology*, will receive the larger share of our attention; it treats of the generation and the movement of storms, the production of clouds and rain, the heating of the air, and the general circulation of the atmosphere.

BIBLIOGRAPHY

General Works on Meteorology

J. HANN's " Lehrbuch der Meteorologie," 1st ed., Leipzig, 1901; 2d ed., Leipzig, 1906, is the most complete digest of current knowledge and opinion in most departments of meteorology. The first edition is rich in bibliographical references; the second is reduced in size, for use as a textbook. Teachers and advanced students who can read German should have access to both. There is no English translation.

Other useful general treatises are:

ANGOT, ALFRED, " Traité élémentaire de météorologie," 2d ed., Paris, 1907.

BEBBER, W. J. VAN, " Lehrbuch der Meteorologie für Studierende und zum Gebrauche in der Praxis," Stuttgart, 1890.

BÖRNSTEIN, R., " Leitfaden der Wetterkunde; gemeinverständlich bearbeitet," 2d ed., Braunschweig, 1906.

DAVIS, WILLIAM MORRIS, " Elementary Meteorology," Boston, 1894.

FERREL, WILLIAM, " Recent Advances in Meteorology, Systematically Arranged in the Form of a Text-book," Washington, 1886. (United States Signal Office, *Annual report of the chief signal officer, 1885.*)

GREELY, A. W., " American Weather," New York, 1888.

MOHN, H., " Grundzüge der Meteorologie," 5th ed., Berlin, 1898.

SCOTT, ROBERT H., " Elementary Meteorology," 4th ed., London, 1887. (*Reprinted* 1903, *etc.*) (International Scientific Series.)

SPRUNG, A., " Lehrbuch der Meteorologie. Im Auftrage der Direktion der Deutschen Seewarte bearbeitet," Hamburg, 1885.

WALDO, FRANK, " Elementary Meteorology for High Schools and Colleges," New York, etc., 1896.

WARD, ROBERT DECOURCY, " Practical Exercises in Elementary Meteorology," Boston, 1899.

More recent than any other general treatise in English is PROFESSOR ABBE's article, " Meteorology," in the New Volumes of the " Encyclopædia Britannica," vol. xxx, 1902; and articles by Profs. Moore, Henry, and others in " Encyclopedia Americana."

Among important meteorological journals may be mentioned the *Bulletin of the Mt. Weather Observatory* and the *Monthly Weather Review*, both published by the U. S. Weather Bureau; *Quarterly Journal of the Royal Meteorological Society*, London; *Symons's Meteorological Magazine*, London; *Journal of the Scottish Meteorological Society*, Edinburgh; *Meteorologische Zeitschrift*, Brunswick; *Das Wetter*, Berlin; *Ciel et Terre*, Brussels; *Bulletin de la Société Belge d'Astronomie*, Brussels; *Annuaire de la Société Météorologique de France*, Paris.

Uniform methods in meteorological work are attained through frequent international meetings of meteorologists, the results of whose deliberations have been brought together in Hildebrandsson and Hellmann's " Codex of Resolutions Adopted at International Meteorological Meetings, 1872–1907," published by the British Meteorological Office, London, 1909.

CHAPTER I

THE ATMOSPHERES OF THE EARTH AND OF THE PLANETS

How Atmospheres are Formed.—Atmosphere (Greek, vaporous sphere). The larger the planet, the longer is the time that must elapse before the heavy vapors of earth and metal, which largely compose its early atmosphere, cool, and congeal into a crust, leaving an attenuated residual of such density and constitution as to permit of the beginning of the forms of life that have inhabited the earth. And, conversely, the smaller the planet is, the sooner will it cool and its atmosphere become suited to the needs of life; and the quicker will the air be combined into the rocks, or dissipated into space, and the earlier will death come to the planet.

THE ATMOSPHERE OF THE SUN.—One can form no adequate picture of the atmosphere of the sun. To the unaided eye it appears as a smooth, bright, quiescent sphere, but the telescope reveals millions of small agitations and hundreds of red flames of hydrogen that shoot outward to distances of hundreds of thousands of miles. The largest of the spots are visible without artificial aid, and during eclipses, when the intense glare of the center of the sun is obscured, the hydrogen flames may easily be seen shooting outward from its rim, which, like the rest of the surface, is in a continual state of terrific agitation.

The first condition necessary for life as we know it is a suitable atmosphere, but before the sun can have this an incomprehensible period will have elapsed, its light will have gone out, its heat will have ceased to reach the earth and the other planets in appreciable quantities, the earth will have been dead millions of years, and the sun itself will only receive heat and light from the feeble rays of the stars that, unlike itself, have not yet ceased to shine; but even then the sun must remain dead, for there is no external source whence it can receive appreciable heat.

ATMOSPHERES OF LARGE PLANETS.—Jupiter, and perhaps Neptune, Uranus, and Saturn, have hot atmospheres still in violent agitation. The earth, millions of years ago, had a similar atmosphere. When the internal energy of these vaporous planets wanes and they cool down to the condition of a crust, it is probable that the simplest forms of life cannot be evolved on them, for they are too far from the sun to receive sufficient life-giving heat. (See Table I.)

ATMOSPHERE OF THE MOON.—The moon already is dead. It shows no refraction or diffusion of light, such as would occur with an atmospheric envelope. If it is formed of matter abandoned by the earth, as it doubtless is, it once must have had an atmosphere, a portion of which was absorbed by its rocks as they cooled, and the remainder lost as the result of the low power of attraction of so small a body, which is insufficient to prevent the darting molecules of gases from shooting off into space. The absence of a protecting cover of air allows the heat of the sun to escape by radiation almost as rapidly as it is received; and the long nights (each as long as fourteen of the earth's days) during which the sun's rays are entirely cut off, probably permit the temperature of the dark side to fall to something like —400° F.

TABLE I.

Relative Intensity of the Sun's Radiation at the Planets.

NAME OF PLANET.	Mean Distance, Taking that of the Earth as Unit.	Relative Intensity of Solar Radiation, Taking that at Earth as Unit.	Absolute Intensity if the Solar Constant Equals 3.0. Calories.[1]
Mercury	0.3871	6.673	20.019
Venus	0.7233	1.912	5.736
Earth	1.0000	1.000	3.000
Mars	1.5237	0.431	1.293
Ceres	2.7673	0.131	0.393
Jupiter	5.2028	0.037	0.111
Saturn	9.5388	0.011	0.033
Uranus	19.1833	0.003	0.009
Neptune	30.0551	0.001	0.003

How Atmospheres are Maintained and How Lost.—Atmospheres undergo a continual change. The processes of Nature are always adding to some of the constituent gases in some ways, and transforming, or taking from them, in other ways. On the earth, at least, the loss and the gain are so nearly equal as to maintain at present a nearly constant condition; marked changes have taken place, however, in long geologic periods. Our early atmosphere probably contained large quantities of carbon dioxide, which were absorbed by the rank vegetable growth that now forms the coal beds of the earth, and the slowly cooling rocks that constitute the crust took in large quantities of oxygen; in fact, nearly one half of the weight of the crust of the earth is composed of the latter element.

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[1] The most recent observations give this value as about 2.1 at the outer surface of the earth's atmosphere.

Present Atmosphere Residual of Earlier Atmospheres.—In consequence it may be said that our present atmosphere is what remained after the earth had absorbed its gases nearly to depletion, and after the lighter gases, like hydrogen and helium, which seem to have too great a molecular velocity to be imprisoned by the earth's attraction of gravitation, had been dissipated into space. Somewhat similar processes may be assumed to be taking place on the other planets, or to have taken place.

Constituent Gases Lost Through Kinetic Energy.—An understanding of how atmospheres are lost through the kinetic energy of molecules requires that careful account be taken of the relations that subsist between the attraction of gravity of planets, their temperatures, and the weights of the molecules of the different gases that compose their atmospheres. The speed of the molecule depends on its temperature and its mass, being less at low temperatures and greater at high temperatures, and light molecules moving more swiftly than heavy ones.

According to the kinetic theory, a gas is composed of molecules that dart about at velocities that, in connection with numerous collisions (seven or eight millions for each molecule near the earth in $\frac{1}{1000}$ of a second) and the energy of each molecule, may allow a certain proportion of them at any one time, to reach velocities so great that, if they pass into the outer layers of the air, where collisions are infrequent, they escape from the attraction of the planet and pass away never to return.

Gases that cannot be held by the moon may be imprisoned by the earth and those that can escape from the earth may be held by the larger planets.

Critical Velocity for the Escape of Molecules.—The work of G. Johnstone Stoney, of England, has shown that the less gravity there is exerted by a planet the greater is the height to which its atmosphere will expand with a given temperature; that if the potential of gravity be sufficiently low and the velocity with which the molecules dart about sufficiently high, individual molecules will dart away from that body and become independent wanderers through space; that a speed of 10.5 kilometers (about seven miles) per second, in a vertical direction, will carry a molecule at the outer boundary of the earth's atmosphere away never to return. This may be called the critical velocity.

CLAUSIUS'S VELOCITY OF MEAN SQUARES is the velocity whose square is the mean of the squares of the velocities of the individual molecules of a gas. Some of the molecules move more slowly and some faster than the mean. Some of them may attain to a velocity largely in excess of the "velocity of mean squares." Especially is this the case when the lighter molecules collide with those of several times their mass at a time when the heavier ones are moving at more than their average speed.

The velocity of mean squares, at a temperature of —66° C., or 87° below zero F. (which temperature is sometimes found at altitudes of above 11,000 meters or 7 miles, where the density of the atmosphere is reduced to about $\frac{7}{25}$ that at the surface), is, by Cook's equation, 1,603 meters per second for hydrogen, 1,133 for helium, and 534 for water vapor. Now, in order to reach the critical velocity, or the velocity of escape from the earth, molecules of hydrogen must be accelerated to 6.55 times, helium to 9.27 times, and water vapor to 19.66 times their respective velocities of mean squares.

GASES THAT ARE IMPRISONED BY THE ATTRACTIONS OF VARIOUS PLANETS.—Since vapor of water does not escape appreciably from the atmosphere of the earth, while helium and hydrogen are both assumed to escape, it has been maintained that any gas having a ratio less than 9.27 will ultimately escape, but gases whose ratio is equal to or greater than 19.66 will be imprisoned indefinitely by the earth in its atmosphere. On the supposition that helium escapes from the earth, it follows that the moon cannot retain an atmosphere whose molecules are less than 19.5 times the mass of the molecules of helium, or 39 times that of hydrogen. Mercury cannot imprison an atmosphere whose molecules are less than 10.25 times the mass of the molecules of helium. Venus can retain an atmosphere similar to that of the earth, while Mars cannot imprison water vapor at a temperature greater than —78.3° C.[1] The planets Jupiter, Saturn, Uranus, and Neptune can each retain an atmosphere whose molecules are less than the molecules of hydrogen.

GASES IMPRISONED BY THE EARTH.—From what has gone before it would appear that the earth's gravitation and the temperature of its outer air are such as to retain without appreciable loss argon, carbon dioxide, oxygen, nitrogen, vapor of water, and ammonia, but that helium and hydrogen escape from the top of the atmosphere about as fast as they are supplied from hot springs and other sources at the bottom. Prof. James Dewar, who in 1893 liquefied air and subsequently froze it into a clear, transparent solid, has shown that helium and hydrogen accumulate in the air near the earth at least in measurable quantities.

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[1] From observations taken by Campbell during the summer of 1909 on the top of Mt. Whitney, Cal., it seems certain that Mars is not supplied with an appreciable amount of water vapor.

Height of the Earth's Atmosphere.—Exact computation has shown that if the air were of the same density at all elevations, which it is not, it would only extend upward a distance of 5 miles. From the ratio of decrease of density with elevation it is known that only 0.028 inch of pressure can be exerted by air at a height of 30 miles, and that at 50 miles the atmosphere must be too tenuous to manifest a measurable pressure; yet it is sufficient, at the latter elevation, to diffract or scatter an appreciable amount of the sun's rays at sunrise and at sunset, thereby affecting the duration of twilight.

The appearances of meteors, which are rendered luminous by rushing into the earth's atmosphere, and whose altitudes have been determined by simultaneous observations at several different places, reveal the presence of air at a height of nearly 200 miles, but not air of a density or composition like that near the earth.

PROPORTION OF GASES NOT THE SAME AT ALL ELEVATIONS.—Statements in the older text-books that the relative proportions of the gases of the air remain constant at all elevations need now to be modified, even though samples of air taken at an altitude of 9 miles have not shown difference in composition. This homogeneity, up to the height of 9 miles, or more, is what should be expected as the result of the constant mixing of the air by cyclonic and anticyclonic action, and by winds in general, which have more or less upward and downward components of motion. But storms operate only in the lower air—mainly below the 6-mile level—and ascending and descending currents cease below the height of 10 miles. With increase in elevation beyond 10 miles we may reasonably assume that the heavier gases steadily lose in proportion to the lighter ones until at about 60 miles practically nothing but hydrogen remains. Certain it is that the heavier gases have a tendency to accumulate in the lower part of any stratum that is not undergoing convectional mixing—such, for instance, as that next above the turbulent region in which storms operate—and that the lighter gases become relatively greater in volume in the higher reaches of a stratum of steady equilibrium. This opinion is strengthened by the spectrum of a meteor that was secured by Professor Pickering;

it revealed an atmosphere of hydrogen and helium, the two lightest of gases.

Distribution of Gases in the Atmosphere.—The accompanying table, calculated by Humphreys[1] according to Ferrel's formula for latitude 45°

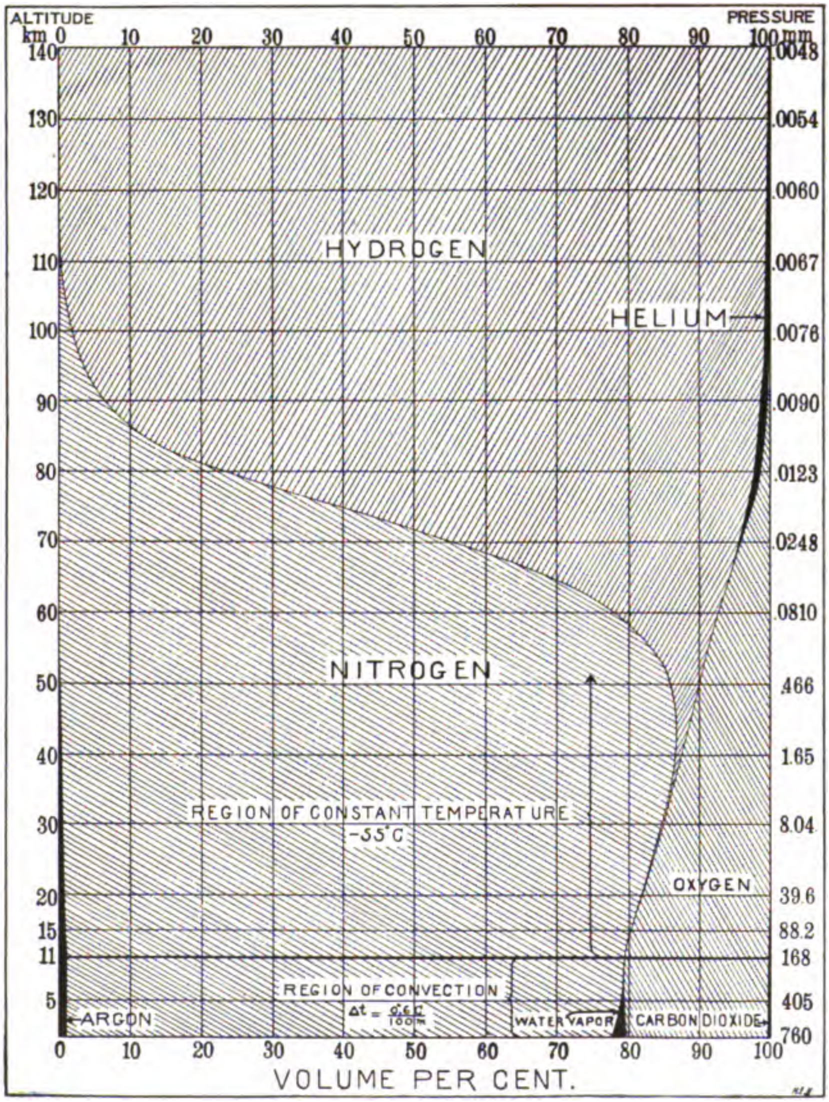

FIG. 1.—DISTRIBUTION OF GASES IN THE ATMOSPHERE (Humphreys).

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[1] *Mount Weather Bulletin*, vol. ii, p. 66, 1909.

and graphically represented in Fig. 1, is based on the following assumptions, which correspond to approximately average conditions:

1. That the several gases in addition to water vapor present to an appreciable extent in the atmosphere, and their volume percentages in dry air at the surface of the earth, are, as Hann[1] gives them:

Nitrogen	78.03	Hydrogen	0.01
Oxygen	20.99	Neon	0.0015
Argon	0.94	Helium	0.00015
Carbon dioxide	0.03		

2. That water vapor is present to the extent of 1.2 per cent of the total gases at the surface of the earth, and that it decreases rapidly with increase of elevation to an imperceptible amount at or below the level of 10 kilometers.

3. That the surface temperature is 11° C.

4. That the temperature decreases uniformly, at the rate of 6° C. per kilometer, from the surface to an elevation of 11 kilometers, where it is —55° C.

5. That beyond 11 kilometers above sea level the temperature remains constant at —55° C.

6. That convection, and therefore constant volume percentage of the gases, except as slightly modified by the presence of water vapor, obtains throughout the region of temperature changes, that is, from the surface up to the region of constant temperature.

7. That in the region of constant temperature, or that above 11 kilometers' elevation, there is no convection, and that therefore in this region the several gases present can and do distribute themselves according to their respective molecular weights.

One of the above-mentioned gases, neon, constitutes only about the $\frac{1}{100}$ part of 1 per cent of the lower atmosphere, and a rapidly decreasing proportion of the upper atmosphere. Therefore, like krypton, xenon, and some others, it is at any altitude too small in amount to appear on the graphical representation.

The ozone, if present in the upper atmosphere, as there is reason to believe it is, probably forms and decomposes over and over again, so that presumably the oxygen settles to rather lower levels and disappears correspondingly earlier than shown by Fig. 1 and Table II.

The distribution of the gases of the upper atmosphere may, in some respects, be distinctly different from that indicated. We know the conditions, and they are as here represented, tolerably accurately below the isothermal region (see Chapter VIII); and we also know something of the conditions of even this region up to about 30 kilometers. We know that in it the winds are much less than they are in the upper portions of the convective region, which lies below it, that they are excessively dry, and that up to 15 kilometers, at least, the composition of the air is sensibly that of dry atmosphere at lower levels. As to the conditions above 30 kilometers we have only such evidence as has been gathered from meteors, from auroras, and from volcanic dust; evidence that gives some knowledge of the direction and speed of the winds in these high altitudes, and that indicates the presence of an appreciable percentage of hydrogen and of helium in the outer atmosphere.

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[1] "Lehrbuch der Meteorologie," 2d ed., p. 5.

Table II and Fig. 1 must therefore be understood to represent both what we know of the lower atmosphere and what we have reason to believe true of the upper.

Particular attention should be given to the relatively small amount of water vapor and to its rapid elimination with increase of elevation; facts which, when its vast importance is considered, are to most people nothing short of astonishing.

TABLE II.

Percentage Distribution of Gases in the Atmosphere.

HEIGHT IN KILOMETERS.	GASES.							Total Pressure in Millimeters.
	Argon.	Nitrogen.	Water Vapor.	Oxygen.	Carbon-dioxide.	Hydrogen.	Helium.	
150						99.73	0.27	0.0043
140						99.70	0.30	0.0048
130		0.02				99.64	0.34	0.0054
120		0.10				99.52	0.38	0.0060
110		0.40		0.02		99.16	0.42	0.0067
100		1.63		0.07		97.84	0.46	0.0076
90		6.57		0.32		92.62	0.49	0.0090
80		22.70		1.38		75.47	0.45	0.0123
70	0.02	53.73		4.05		41.95	0.27	0.0248
60	0.04	78.16		7.32		14.33	0.15	0.0810
50	0.08	86.16		10.01		3.72	0.03	0.466
40	0.16	86.51		12.45		0.88		1.65
30	0.22	84.48		15.10		0.20		8.04
20	0.55	81.34		18.05	0.01	0.05		39.6
15	0.74	79.56		19.66	0.02	0.02		88.2
11	0.94	78.02	0.01	20.99	0.03	0.01		168
5	0.94	77.89	0.18	20.95	0.03	0.01		405
0	0.93	77.08	1.20	20.75	0.03	0.01		760

To avoid getting an erroneous impression, the reader must bear in mind that the figure represents volume percentages. The total pressure is given on the right-hand side, and shows, for instance, that where hydrogen becomes 90 per cent of the total atmosphere, the pressure is only about the $\frac{1}{100000}$ that at sea level.

Vaporous Atmosphere Confined to Lower Air.—It is pertinent here to state that, notwithstanding the lightness of water vapor, whose density is 0.6 relative to dry air at the same temperature and pressure, it is largely confined to comparatively low levels, by reason of the fact that it is precipitated as water by the cold found at only moderate elevations. An approximate idea may be formed of the limit of height and the density of the vaporous atmosphere from the statement that air, even if it be saturated, can contain no more than 0.48 grains of moisture to the cubic foot at zero F. temperature, and this degree of cold probably always occurs, even over the equator, at an altitude of less than 5 miles. It is reasonable, therefore, to suppose that the vaporous air does not exist in appreciable quantities beyond an altitude of 12 miles over the equator, and that a surface defining its upper limits would, from about this elevation, slope downward toward the poles, and rise and fall with the seasons, the amplitude of the movement increasing with latitude.

Optical Methods of Determining the Height of the Atmosphere.—Several methods, based upon optical phenomena, for determining the approximate height of the atmosphere have been suggested and used. The most reliable of these are:

1. Noting the time of the appearance of the morning and the disappearance of the evening twilight arches. These are due to the scattering of light by the upper atmosphere and are just visible when the sun is about 16° below the horizon. From this it is calculated that at an elevation of 40 miles the atmosphere is sufficiently dense perceptibly to scatter or diffract sunlight.

2. Measuring the parallax of meteor trains as simultaneously seen from different places. When a meteor enters the atmosphere it is so heated, because of its great velocity, as to become intensely luminous; but because of its proximity to the earth it appears to have one path among the stars to one observer and a different one to another. The direction and distance of one observer from the other, together with the apparent positions among the stars of the meteor train, furnish data by which the elevation of the meteor during the period of its luminosity can be calculated. In this way reliable observations have given 188 miles (300 kilometers) as

the height to which the atmosphere certainly extends with density sufficient to retard the speed of meteors and to render them luminous.

BIBLIOGRAPHY

STONEY, G. JOHNSTONE, "Atmospheres Upon Planets and Satellites," *Astrophysical Journal*, January, 1898, pp. 25–54.

COOK, S. R., "The Escape of Gases from Planetary Atmospheres, According to the Kinetic Theory," *Astrophysical Journal*, January, 1900, pp. 36–43.

STONEY, G. JOHNSTONE, "The Escape of Gases from Planetary Atmospheres, According to the Kinetic Theory," *Astrophysical Journal*, Part I, May, 1900, pp. 251–258; Part II, June, 1900, pp. 357–372.

COOK, S. R., "The Permanence of the Planetary Atmospheres, According to the Kinetic Theory of Gases," *Monthly Weather Review*, August, 1902, pp. 401–407; September, 1902, p. 406.

STONEY, G. JOHNSTONE, "Escape of Gases from the Atmosphere," *London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, 6th series, vol. vii, June, 1904, p. 620; *Monthly Weather Review*, January, 1905, xxxiii, pp. 6–9.

CHAPTER II

ATMOSPHERIC AIR

Earth's Important Atmospheres.—The earth is surrounded by four important atmospheres—nitrogen, oxygen, vapor of water, and carbon dioxide—and others of less importance, each comporting itself, in accordance with Dalton's law, practically as it would do if the others were not present, except that its rate of diffusion is retarded by their presence. This composite is atmospheric air—usually called *air.* It can be easily compressed, because there is space between its molecules, which are in constant vibration. A doubling of its pressure reduces its volume to one half. This is in accordance with the law discovered independently by Boyle and Mariotte, which is as follows: *The temperature remaining the same, the volume of a given quantity of gas is inversely as the pressure that bears upon it.*

Constituent Gases of the Air.—Air is composed almost entirely of oxygen and nitrogen, mechanically mixed and not in chemical combination. Both by volume and by mass these are the two principal atmospheres. In general, the proportion by volume is about 21 parts of oxygen to 78 parts of nitrogen. But it should not be thought that because some of the other constituent gases are relatively small in amount they are not vitally important in the carrying on of the functions that Nature seems to have assigned to the air. In addition to oxygen and nitrogen, air contains small amounts of many other substances—vapor of water (aqueous vapor), carbon dioxide, argon, nitric acid, ammonia, ozone, hydrogen, helium, xenon, krypton and neon; as well as organic matter, germs, and dust in suspension. Over the land it contains sulphates in minute quantities, and over the sea and near the seashore salt left from the evaporated spray can always be detected. The relative proportions of the gases of the air are practically the same in all parts of the open country.

Since the molecular weight of each component of the atmosphere is different from that of any other, therefore its proportion by volume of the total atmosphere is different from its proportion by weight. For the more abundant gases these two percentages are as follows:

	By Volume.	By Weight.
Nitrogen	78.04	75.46
Oxygen	20.99	23.19
Argon	0.94	1.30
Carbon dioxide	0.03	0.05
	100.00	100.00

NITROGEN.—The greatest by volume of the four atmospheres is nitrogen. This is a nonmetallic, inert gas, which does not manifest many marked chemical affinities, although, in various ways, it may be made to combine with other elements. Its principal functions are to dilute the oxygen and to furnish food for vegetation. It exists in nature in the free state, and also in chemical combination with numerous metals. Its atomic weight is 13.93, if hydrogen = 1. Under a pressure of 35 atmospheres it liquefies at 231° F. below zero. Its inertness is shown by the fact that it will neither support combustion nor burn.

OXYGEN.—Oxygen, also, is a nonmetallic gas. It is second by volume to nitrogen, but, unlike it, is an active element that readily enters into direct combination with many other elements, and it is abundant in nature. Mechanically mixed with free nitrogen, it constitutes about 21 per cent by volume of the air and about 23 per cent by weight. It is, therefore, specifically denser than air. Its atomic weight is 15.88, if hydrogen = 1. In chemical combination with hydrogen, it constitutes $\frac{8}{9}$, by weight, of pure water; combined with other elements it composes 40 to 50 per cent of the crust of the earth. It actively supports combustion—so much so that if it were not greatly diluted with an inert gas, such as nitrogen, it would be difficult for any agencies now controlled by man to quench a conflagration when once started. A piece of steel sputters and burns like tinder when brought in contact with a lighted taper under liquid air, where the supply of oxygen has been increased by its condensation. Oxygen liquefies at —182° F. under a pressure of 50.8 atmospheres.

In free air up to the height of about ten miles there is no appreciable variation in the percentage of oxygen, except that it is slightly greater for northerly than for southerly winds. This possibly may be due to the fact that northwest winds have a downward component of motion, and this motion has a tendency to bring down ozone (see p. 24). Variations of great importance to health and life occur in places where ventilation is restricted, and especially where living creatures exist in closed rooms, and where combustion occurs in confined places. An inspection of the values given in Table III should be sufficient to cause one ever after to give close attention to the condition of the air that he breathes.

TABLE III.

Oxygen in the Air.

(From "Air and Rain," by Robert Angus Smith.)

	Volume Per Cent.
Northeast seashore and open heath (Scotland)	20.9990
Low parts of Perth	20.9350
London, open places, summer	20.9500
After six hours in a small room with a petroleum lamp	20.8300
Pit of theater, 11.30 P.M	20.7400
Court of Queen's Bench, February 2, 1866	20.6500
In pits in a mine	20.1400
When candles go out in a mine	18.5000
The worst specimen yet examined in a mine	18.2700
Very difficult to remain in many minutes	17.2000

Many analyses have shown that oxygen over putrid substances is absorbed, while carbonic acid and other gases are given out. This, in connection with the consumption of oxygen by living creatures, explains the deficiency of oxygen over cities, which is more marked when the air is moving but little, and where the city is located in a depression, or near swampy lands.

Respiration is a vital function in the life of animals and plants. Both these inhale oxygen, a part of which combines with some of the substances of the animal or the plant, forming carbon dioxide, which is exhaled with the unchanged nitrogen. The process is common to all living organisms and automatically proceeds both night and day. It should not be confused with the opposite action of plants in taking in and decomposing carbon dioxide under the influence of sunlight and expelling pure oxygen.

CARBON DIOXIDE (CARBONIC-ACID GAS).—This is another of the four principal atmospheres. It is as important in sustaining vegetable life as oxygen is in supporting animal life, for it forms the chief food supply of all green-leaved plants. December, January, and February show a considerable decrease in the relative amount as compared with June, July, and August; Saussure gives the relation as 77 to 100. The percentage is subject to continual change, and shows both an annual and a diurnal maximum and minimum. In the open country the amount averages about 0.035 per cent by volume, and its diurnal variation is equal to about $\frac{1}{8}$ of its total amount. Vegetation, in addition to the inhalation of oxygen and the expiration of carbon dioxide at all hours, absorbs this gas during the day, and under the influence of sunlight the green granular matter that constitutes the chlorophyll of the cells of the leaves decomposes it, the plant retaining the carbon and giving out the oxygen; but at night, because of the absence of sunshine, the chemical activities of the plant are altered, and the absorption of carbon dioxide ceases; therefore the maximum amount occurs during the nighttime over the land. Over the sea the conditions are reversed and the greater amount, 0.05 per cent, by volume, occurs about midday, while the amount at midnight is about 0.03 per cent. This is because the gas is dissolved in the sea water and is given off with a rise in temperature. There seems to be slightly more of the gas at sea level than at moderate altitudes (1,000 to 4,000 feet).

In cities the amount of carbon dioxide is considerably greater than in the country, frequently rising to 0.07 per cent by volume, and even to 0.10 per cent when there is little wind to scatter what accumulates near the ground. In crowded theaters Angus Smith found as much as 0.32 per cent, and in mines 2.5 per cent. The latter amount would soon be destructive to animal life; in fact, any quantity in excess of 0.06 per cent, especially if combined with the organic matter exhaled from the lungs and from the pores of the skin by animals and man, is injurious to health.

The gas is 1.50 times as dense as an equal volume of air. Its greater density causes it to collect in mines, sewers, cellars, and other low and confined places, unless there is forceful ventilation. The sweep of the American cold wave, with its heavy air moving at a high velocity, is highly beneficial, because it searches into cracks, crevices, and inclosures that are not hermetically sealed, and expels the foul air. All nature feels the revivifying effects of rain and high wind; one washes out the carbonic-acid gas (carbon dioxide) from the air, with the dust and other particles in suspension; and the other enters our habitations and drives out the poisonous atmospheric accumulations. It cannot be too strongly impressed upon the reader's mind that oxygen, the life-sustaining principle of the air, decreases, and carbon dioxide, a poison, increases in air that is breathed, or in air in which candles, lamps, or gas jets are burning; and that all places of habitation, especially those that are used for sleeping rooms, should have a continuous supply of fresh air. The amount should be at least 2,000 cubic feet per hour for each person.

The air receives carbon dioxide from several different sources, the principal of which are the decomposition of vegetable and animal matter, the combustion of fuel, and the respiration of plants and animals. This gas can be liquefied readily by the application of pressure at any temperature less than 90° F.

TABLE IV.

Carbonic Acid in the Air.

(From Robert Angus Smith's "Air and Rain.")

	Volume Per Cent.
In mines, largest amount found in Cornwall	2.5000
Average of 339 analyses from mines	0.7850
In theaters, worst parts, as much as	0.3200
In workshops, down to	0.3000
Manchester during fogs	0.0679
Manchester streets during ordinary weather	0.0403
Manchester where fields begin	0.0369
On hills in Scotland, 1,000 to 4,400 feet high	0.0332

WATER VAPOR may vary in amount from a fraction of 1 per cent for the arid regions to 5 per cent of the weight of the air for the warm humid regions. It is a little over one half as dense as atmospheric air. Its marvelous capacity for the absorption of heat causes it to be an important factor in many meteorological processes. It is another of the four important atmospheres referred to at the opening of this chapter. It occupies space nearly the same as though the other atmospheres were not present, practically the same amount being necessary to saturate a given space, whether it be a vacuum or whether it be filled with air, provided the temperature in both cases be the same. With each increase of 18° to 20° of temperature the capacity of space, or air, for water vapor is doubled. Thus, on a cold day in winter it may form no more than the $\frac{1}{1000}$ part of the air, but on a hot day in summer, near or over large bodies of water, it may, as previously stated, constitute as much as $\frac{1}{20}$ part by weight of the lower air.

Why Called Water Vapor Instead of a Gas.—One of the marked characteristics of aqueous vapor is its sensitiveness to heat, changing from a solid to a liquid, and from a liquid to a gas within a small part of the total range of the thermometric scale. If the air be near the saturation point it requires but a slight lowering of the temperature to precipitate a part of its water vapor in the form of dew, frost, rain, hail, or snow; this is the reason it is usually called *water vapor* instead of a gas. A gas, such as hydrogen or oxygen, has been defined as a fluid above its critical temperature; and the critical temperature of a fluid is that above which it cannot be liquefied by any pressure. Water vapor may be precipitated as frost or snow without passing through the liquid state, and ice and snow may change directly from the solid to the gaseous form.

Saturation.—When the air has taken up all the moisture in the form of water vapor that it can contain at a given temperature it is said to be *saturated.* After saturation is reached no further accumulation can occur, no matter how freely the air may have access to moisture, or what the temperature may be, unless there be an increase in the temperature; and there can be no lowering of the temperature without a corresponding decrease in the amount of water vapor, or *vapor density,*[1] and a return of some water vapor to the liquid state, even though evaporation continues, as we believe, under all conditions of temperature and of vapor density. This is due to the fact that condensation is just as continuous as is evaporation, and that under certain definite conditions of temperature and vapor density, or temperature and vapor pressure, these two balance each other.

Saturation seldom occurs in free air, even over the ocean, except during the prevalence of a dense fog, or inside of a cloud from which rain or snow is falling, or within the thin stratum of air that by contact with a cold surface has had its temperature lowered to the point of precipitation. Even during heavy downpours of rain the air near the earth is usually capable of evaporating some of the rain that is falling through it. In fact, light precipitation may be entirely taken up by the lower air and never reach the earth.

The dew point is the temperature of saturation.

The relative humidity is expressed in percentages of the amount necessary to saturate. At a temperature of 32° F., air resting over a moist surface may continue to increase the amount of its vapor of water until it contains 2.11 grains per cubic foot, which amount is sufficient to exert a pressure in all directions equal to the downward pressure of 0.18 inch of mercury; it will then be saturated and its relative humidity will be 100 per cent. The point to which attention is especially directed is that the pressure of 0.18 indicates the maximum pressure of water vapor at 32° temperature, and any further evaporation must be accompanied by an equal amount of condensation. Now, if this same air be suddenly raised in temperature to 51° its capacity per cubic foot will be increased to twice what it was at 32°, the 2.11 grains will only be equal to one half the number necessary to saturate, and the relative humidity be expressed by 50 per cent instead of 100 per cent. But this latter condition would only exist for an instant, for at the new temperature of 51° air is not saturated until its water vapor exerts a pressure equal to 0.37 inch of mercury, when it will contain 4.22 grains per cubic foot. A gain in the moisture content, therefore, begins anew as soon as the temperature has been increased, and may continue until saturation is reached at the higher temperature. At 70° the vapor pressure of saturation is 0.73, which is about double what it is at 50°, and the amount of water vapor necessary to saturate is 7.98 grains, which also is about twice the amount required at 50°. At 90° the vapor tension that corresponds to saturation is 1.41, and the greatest amount of water vapor that can be held is 14.79 grains per cubic foot.

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[1] Amount (mass) of vapor per unit volume.

The relative humidity of the air increases during the night, as the result of falling temperature, although the actual amount of vapor of water may be less than during the day. This increase in relative humidity is much more pronounced in the country than in the city, as the absence of pavements and brick buildings allows a freer loss of heat.

The absolute humidity is expressed in grains the cubic foot, or by the pressure in inches of mercury.

The Hygrometer measures the amount of water vapor.

ARGON.—A gas that exhibits an entire lack of chemical affinity. As nitrogen also is inert, argon remained concealed in it until the exhaustive researches of Lord Rayleigh and Prof. William Ramsay discovered its presence in 1894. For this they were awarded the Hodgkins medal and also the grand prize by the Smithsonian Institution. Before the publication of their investigations chemists usually had estimated the amount of nitrogen by removing all such active gases as oxygen, ammonia, and carbon dioxide and assuming that all that remained was nitrogen. But Rayleigh found that this residual, when compared with nitrogen prepared from ammonia, was about $\frac{1}{200}$ denser than the latter. This fact led him to designate the first as *atmospheric nitrogen* and the other as *chemical nitrogen.* Nitrogen secured from several different compounds had all the same density, but all specimens of nitrogen prepared from the air consistently differed from them by being greater in density by the amount of 1 part in 200. This logically led to the conclusion that atmospheric nitrogen was mixed with some other inert gas of greater density than itself, which a short time afterwards was clearly identified and named *argon.* Air contains 0.937 of 1 per cent, by volume, of argon. It is probable that a molecule of this gas contains but one atom; if this be true, then its atomic weight, as compared with hydrogen, is 39.60. Its critical temperature is —184° F. At this temperature it liquefies under a pressure of 40 atmospheres. The density of argon is represented by 1.212, that of air being 1.

HYDROGEN (Greek, *hudor*, water; and *gennao*, generate).—It is an odorless gas, which, while not poisonous, cannot support life. One may breathe considerable quantities of it, when mixed with a sufficient quantity of atmospheric air, without inconvenience. Under certain conditions it combines with some other substances, but it does not possess marked chemical properties. It is the lightest of all known gases. Its density, ordinary air being taken as unity, is 0.0692. It is combustible, and when 1 volume of oxygen, or 5 volumes of atmospheric air, are mixed with 2 volumes of hydrogen, the mixture violently explodes when ignited. Oxygen and hydrogen combine to form water, and when the union is effected by combustion the water instantaneously expands into steam, as the result of the sudden application of extreme heat, but quickly condenses after the explosion. In stating the atomic weights of the different elements, hydrogen is usually taken to represent unity, as its atom is the lightest of any known substance. For various purposes of comparison it is convenient to assume that the atomic weight of oxygen is 16, instead of 15.88; this is equivalent to making the atomic weight of hydrogen 1.0076. Hydrogen monoxide (water) is the most abundant of all compounds and a necessary part of nearly every organic tissue. Free hydrogen is supplied to the air in small amounts by active volcanoes and in other ways, but the speed of its molecules is such that they probably readily escape from the earth's attraction. The loss from the upper air into space is thought by Stoney to be equal to the gain at the bottom of the air, where the amount present is minute, according to Dewar never more than $\frac{1}{100000}$ part by volume. Water is produced as the result of the burning of hydrogen in air or oxygen. Its critical temperature is about —373° F., at which it liquefies under the pressure of 15 atmospheres.

XENON.—An inert gas discovered in 1898 by Ramsay and Travers, in their experiments with argon. Its atomic weight is 127, and it forms but a minute part of the air.

HELIUM.—An inert gas whose discovery was made possible by the segregating of argon from nitrogen. The spectroscope had revealed its presence in the sun a number of years before it was discovered on the earth. The name is derived from the Greek word *helios*, meaning the sun. Helium is given off by some hot springs, and radium appears to have the property of continuously generating it. It has about $\frac{1}{8}$ the density of oxygen, and the speed of its molecules is such that it probably escapes from the earth's attraction so readily that it does not accumulate in the free air in considerable quantities, Dewar giving the amount as not less than $\frac{1}{352000}$ part by volume. Its atomic weight is 4.00, hydrogen equaling 1. Its critical temperature is very low, even nearer to absolute zero than that of hydrogen. It is, therefore, extremely difficult to reduce it to the liquid form.

KRYPTON is another inert gas that, like neon and xenon, was with difficulty separated from argon by Ramsay and Travers in 1898. Its name was derived from a Greek word that signifies *hidden*. Its density, as compared with hydrogen, seems to be 40.75, and its atomic weight 81.5. Krypton constitutes about one part in a million of the air.

NEON.—The discovery of argon led to the discovery of neon. It was found by Ramsay and Travers in liquid argon in 1898. As compared with hydrogen, its density is about 9.96, and its atomic weight 19.92. It constitutes but a minute part of the bulk of the air, the amount being from $\frac{1}{50000}$ to $\frac{1}{100000}$ part. Its name is from a Greek word, the meaning of which is *new*.

AMMONIA is a compound of hydrogen and nitrogen, having the formula NH_3. The quantity in the air is minute, amounting to only about 1 part in 28,000,000 parts of air. It is supplied to the air by the rotting of organic matter, the combustion of coal, and the vinous fermentations. Large quantities of it were formerly secured for commercial purposes by the destructive distillation of hides, hoofs, and horns, but now the main source of supply is from the manufacture of coal gas, it being one of the by-products. Ammonia is found in rain water, and the air is washed clean of it during downpours of rain. Water at freezing temperature and ordinary pressure is capable of absorbing 1,148 times its own volume of ammoniacal gas, forming *liquor ammoniæ*, or *spirits of hartshorn*. Cold and pressure will liquefy gaseous ammonia, which event occurs at a freezing temperature under a pressure of 4.4 atmospheres. At about $-29°$ F. it liquefies at ordinary air pressure.

NITRIC ACID.—After thunderstorms traces of nitric acid may be found in rain water. It is the result of combining with water one of the five compounds that oxygen forms with nitrogen. Its formula is HNO_3. This acid is energetic in its action on organic matter. On a small scale, an imitation of what occurs in free air may be accomplished in the laboratory by discharging electricity into a mixture of oxygen and nitrogen in the presence of water. The strongest concentration of the acid freezes at about —50° F. and boils at about 187° F.; it may have a specific gravity[1] as high as 1.55. Nitric acid is largely used in the chemical industries.

OZONE (Greek, *ozo,* I smell).—Ozone was first discovered by Dr. Schönbein in 1848. The quantity in the air depends on the environment of the place; in the country the amount averages about 1 part in 700,000 parts of air. By weight the relation is about 1 to 450,000, according to Houzeau.

Ozone is formed in the laboratory by passing an electric charge through oxygen or atmospheric air, and in nature by the disruptive discharge of lightning, or by the silent action upon oxygen of ultra-violet rays and of the great amount of electricity present in the upper air, and possibly by the evaporation of clouds, fog, and water near or at the earth. Molecules of oxygen are thus broken up and the parts recombined in such manner that each molecule contains 3 atoms, instead of the 2 that originally composed its parts. Ozone is, therefore, oxygen in an allotropic[2] state; it is representative of a special arrangement of the atoms just as carbon forms the pellucid diamond or the opaque charcoal with the same constituent matter.

Ozone an Active Sanitary Agent.—Like *chlorine,* ozone has powerful bleaching and disinfecting properties. Its density is 1.5, oxygen equaling 1. By reason of the unstable condition of the molecular structure it is a much more active oxidizing agent than oxygen; and this fact in part accounts for the less amount observed in the air near the ground, and for the almost total absence of ozone from the air over large cities, where decaying organic matter exists at all times in comparatively large quantities, the ozone rapidly entering into chemical union with that which is in process of decay.

According to Schönbein, air containing so little ozone as 1 part to 3,240,000 parts of air is capable of purifying its own volume of air containing the noxious effluvia evolved in one minute from 4 ounces of highly putrid flesh. It is neutralized in the process, and, therefore, ceases to exist as ozone.

Effect of Ozone on Animal Life.—While ozone, in the minute percentage found in nature, is healthful, it has a highly irritating effect on the mucous surfaces of the respiratory passages when breathed in a condensed form, and the quantity is not large that will thus cause the death of any animal confined in the air containing it.

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[1] Its weight in comparison to the weight of an equal volume of water.

[2] Capable of existing in several forms.

It may be that the invigorating effects of the clear, crisp air of a frosty morning, and of the dry air of the cold waves of winter, are due to the great amount of ozone and electricity in the air; and may not the healthfulness of mountain air be due to the increase with elevation in the quantity of ozone and electricity, as well as to the less quantity of water vapor, dust, and disease germs? Sea air also is rich in ozone, and deficient in dust; but it is humid.

Diurnal Variations in Ozone.—Two maximum periods may be observed each day, which agree closely with the diurnal variations in atmospheric electricity—one between 4 and 9 A.M., and another between 7 and 9 P.M. The minima occur between 10 A.M. and 1 P.M., and between 10 P.M. and midnight.

Seasonal Variations in Ozone.—The results of four years' observations at the State Agricultural College, Michigan, are graphically shown in Fig. 2. This indicates that the amount of ozone varies with the season, the winter furnishing a quantity greatly in excess of that of the summer. This variation is only partly accounted for by the absorption of ozone by the greater quantity of putrescible matter present during the summer. The principal cause is the greater energy of winter storms as compared with those of summer, by which the air is mixed, the anticyclones, or cool waves, bringing down from above electricity and ozone.

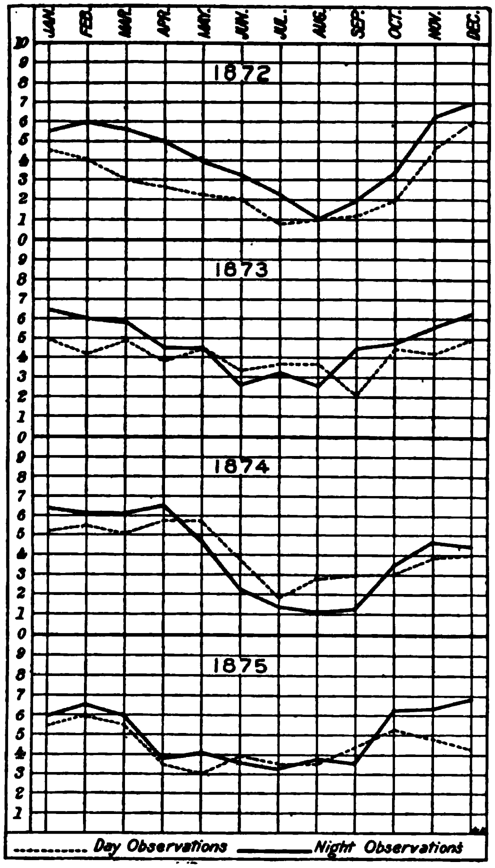

FIG. 2.—SEASONAL VARIATIONS IN OZONE (Kedzie).

Thunderstorms Generate Ozone.—The downrush of cold air that occurs in the local storms of summer temporarily increases the amount of ozone in the lower air. But the area affected by a summer storm is small and its effect soon disappears. Low-hanging clouds, with frequent discharges of electricity between them, or between them and the earth, often generate so much ozone that the odor is pronounced for hours after.

Amount of Ozone Varies Widely With Environment.—Fig. 3 gives a graphic representation of the comparative amount of ozone over a swamp and in an open field, the field showing a marked excess over that of the swamp.

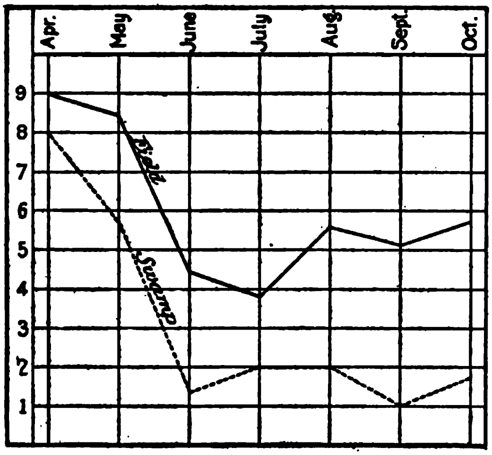

FIG. 3.—OZONE OVER FIELD AND OVER SWAMP (Kedzie).

The amount of ozone is greater over the sea than over the land, probably due to the absence of oxidizable matter, which allows the ozone to accumulate.

While no method of measuring the quantity of ozone in the air has yet been devised that is not subject to grave errors, the observations seem to justify the conclusion that it is present in greater amount during windy and rainy or snowy weather than during calm and dry weather. Wolf makes the following comparison: Fine days, 4.19; rainy days, 11.40; and snowy days, 14.15. It is more abundant with westerly than with easterly winds, which is due to the fact that westerly winds have a downward component of motion. If the westerly winds be weak and the easterly winds come from over large bodies of water the conditions may be reversed.

Ozone is always found about waterfalls and in the presence of large spraying fountains; and the streaming of electricity from the projecting points of leaves possibly is a source of ozone.

The researches of Mr. Joseph Baxendell, F.R.A.S., of England, indicate that the amount of ozone bears some relation to the transparency of the lower air; that when fog or dense haze is present it usually is impossible to obtain the faintest trace of ozone, but that it manifests itself on the evaporation of the fog or the clearing away of the haze.

Methods of Measuring the Quantity of Ozone.—Several chemical tests have been employed for measuring the relative quantity of ozone present in the atmosphere. Schönbein proposes the three following: (1) The production of free iodine and potassium hydrate from potassium iodide; (2) The oxidation of thallous to thallic oxide; (3) The oxidation of manganous to manganic oxide.

The first of these is the test most commonly employed. A paste is prepared by adding 10 parts of the best quality of starch to 200 parts of pure water, heating this until the starch gelatinizes, and then dissolving in it 1 part of pure iodide of potassium. This paste is then spread evenly on sheets of paper free from sizing, which are then rapidly dried without exposure to sunlight.

A slip of this paper ½ inch wide and 4 inches long is moistened in pure water and suspended where it will be screened from the sun, but exposed to diffuse daylight and to the air. The inside of the standard instrument shelter of the Weather Bureau is probably the best exposure obtainable. After being exposed for from eight to twelve hours the paper is taken down and dipped in water, and its color compared with a standard ozone scale of colors, arranged on a scale of 1 to 10.

The objection to this method is, as shown by Schönbein, that hydrogen peroxide (H_2O_2) as well as ozone reacts upon this paper, which is also hygroscopic, its indications varying with the relative humidity of the atmosphere.

Liquid Air.—Within recent years every known gas has been liquefied, including helium. Most matter can be readily changed from the solid to the liquid state, and from the liquid to the gaseous by the application of heat. The problem of the liquefaction of gases is mainly one of producing extreme cold. This is now best accomplished by causing a gas that has been cooled by expansion to circulate about the pipes containing the gas that is to be liquefied. Liquid air has about the same color and specific gravity as water. At ordinary pressure it boils at —312° F.

BIBLIOGRAPHY

HANN, J., "Handbook of Climatology," translated by R. DeC. Ward, New York, etc., 1903, pp. 74–83.

RENK, FRIEDRICH, "Die Luft," Leipzig, 1886. (Pettenkofer & Ziemssen, "Handbuch der Hygiene und der Gewerbekrankheiten," 1. Teil; 2. Abteilung; 2. Heft.)

RAMSAY, SIR WILLIAM, "The Gases of the Atmosphere; the History of their Discovery," 3d ed., London, 1905.

"Smithsonian Meteorological Tables," Edition of 1907, Washington, D. C.

CHAPTER III

MICROÖRGANISMS AND DUST-MOTES OF THE AIR

Bacteria in the Air.—Microörganisms, or microbes, float in the air. They are of the pathogenic, or disease-producing, type, and of the non-pathogenic varieties, such as the molds that produce ferments. The air transports vast unseen armies of such workers. Some of them are enemies; others are benefactors of the human race. The beneficent varieties are active in clearing away the refuse of animal and vegetable life, in fixing fertilizing gases in the soil, in giving flavor to fruits and proper growth to leguminous crops, in transforming the crudest must into the best claret, and the poorest tobacco leaf into the fragrant Havana; in curing cheese and butter and in fermenting beer, and in a multitude of other useful employments. The virulent varieties, if they gain lodgment in suitable human tissues before the sunlight kills them or weakens their virility, disseminate the zymotic diseases.

BACTERIA DECREASE WITH SUNSHINE AND VENTILATION.—Few disease-producing or other bacteria are found in the air of mountains, or in that of the ocean; and there are many less in the air of the open country than in that of the city. At Montsouris observatory the average number of bacteria in a cubic meter of air has been found to be 345, while in the city of Paris, ten miles away, the number was 4,790.

The number is small in well-ventilated city houses that let an abundance of sunlight into their interiors, but is large in crowded tenements.

An elaborate series of observations, by Carnelley, Haldane, and Anderson, on the number of bacteria in the air of houses in the poorest parts of Dundee, Scotland, between the hours of 12.30 A.M. and 4.30 A.M., showed that in one-room tenements, where as many as six persons occupy one bed, there were, on an average, 60 microbes to 1 quart of air; in two-room houses, 46; and in houses of four rooms, and more, only 9. They found an increase in the death rate of those occupying these quarters in direct proportion to the microörganisms in the air; but they called attention to the fact that the occupants of the more crowded quarters had poorer food and less of it than the others, and that other sanitary conditions, besides those of air, grow worse with decrease of space per person.

The effect of vitiated air on mortality is more clearly shown in the case of the certified mortality statistics of the British army cited by Mrs. Percy Franklin, in her book on "Bacteria in Daily Life," page 55. In the period 1830–46 the death rate for phthisis was 7.86 the 1,000. Then a considerable increase in air space to the man was allowed in the barracks, and the rate for the disease for the period 1859–66 fell to only 3.1 the 1,000. But the amount of sunshine may be nearly as important as the quantity of air, for most of the microbes of disease quickly die, or are rendered less virulent, under its influence.

The following table, prepared by M. Miquel, shows the richness in bacteria of the air in the principal localities hitherto examined:

TABLE V.

LOCALITIES.	Bacteria per Cubic Meter. (Meter= 39.37 Inches.)
Sea air (Atlantic Ocean)	0.6
Air of the high mountains	1.0
Air in the saloons of vessels	60.0
Air taken at the top of the Pantheon in Paris, 272 feet above ground	200.0
Air park of Montsouris	480.0
Air City of Bern	580.0
Air Rue de Rivoli (Paris)	3480.0
Air new houses in Paris	4500.0
Air sewers in Paris	6000.0
Air Laboratory of Montsouris	7420.0
Air old houses in Paris	36000.0
Air new Hôtel Dieu (hospital), Paris	40000.0
Air hospital "de Pitié," Paris	79000.0

As previously stated, the number of living organisms diminishes as one goes farther from cities, or ascends a mountain, or rises above the ground into the air. The observations that M. de Freudenreich has made between altitudes of 6,560 and 13,120 feet establish this fact, as do the observations of several other trustworthy observers. In a cubic meter of air taken from the summit of Theodule Pass, at an altitude of 10,830 feet, he found only 1 bacterium; in a second measurement he found 1 bacillus and 1 micrococcus in 2 cubic meters of air taken at the same place. A third time he found that in 2,700 cubic meters of air taken at the same altitude, there were no bacteria. Two other experiments made at the summit of Niesen, 7,760 feet, near the lake of Thun, gave him analogous results.

OCEAN AIR AS FREE FROM BACTERIA AS THAT OF HIGH MOUNTAINS.—The purity of the air of high mountains, so far as it concerns microbes, does not surpass the purity of the ocean air, which contains, on the average, only 5 or 6 bacteria per 10 cubic meters.

ICE AND SNOW CONTAIN BACTERIA.—They exist in small numbers, if at all, at altitudes where snow forms, but it gathers them as it falls through the lower air. Ice forms at the surface of water, or about numerous small particles in suspension, which rise at once to the top as soon as the water congeals about them in the form of buoyant coverings; meanwhile sediment is continually settling to the bottom, carrying bacteria with it. Ice will form more readily in quiet water, where sedimentation has been most rapid, and where, therefore, there are the fewest bacteria in position to be included. Some experiments have indicated that ice contains not over 90 per cent of the average number of bacteria present in a like volume of the water from which ice is formed.

Observations at different places have shown that more disease germs exist in river water in winter than in summer, which may be due to the greater disinfecting power of the sun's rays in summer.

Dust in the Air.—The sources of atmospheric dust are volcanoes, meteors, combustion, salts from the spray of the ocean, and small particles of matter lifted from the earth by winds. Dust rains into the atmosphere from outer space, as the earth pursues its course about the sun. Meteors that are consumed through the heat generated by striking into our air contribute to the supply.

The dust from the eruption of Krakatoa was shot high into the air and was wafted entirely around the world, falling on the decks of ships and on various parts of the earth. It affected the color of the sky for months after the explosion. (See Chapter XIV.)

DUST-MOTES MOST NUMEROUS IN CITIES.—The number of dust particles in the air varies greatly with the locality, being least on the ocean and on mountain tops and high in the free air, and greatest in cities, where smoke befouls the air with inorganic substances and sulphurous gases and screens off the disinfecting sunshine.

Mr. John Aitken has conducted elaborate and valuable experiments to determine the number of dust particles in the air. Among these was one made at an elevation of 500 feet just outside the city of Cannes, France, when a strong west wind was blowing from over the Esterel mountains and the air seemed to be pure. The number of particles noted was only 1,600 per cubic centimeter. Two days later, when the wind had shifted and was blowing direct from the town, bringing with it the products of combustion, the number was 150,000. Tests made at many other places showed a similar condition to exist in air coming from the vicinity of cities or towns. The air of large cities invariably shows hundreds of thousands of dust-motes to the cubic centimeter, that of the village or town thousands, and that of the open country at least hundreds.

DIFFUSE LIGHT MAINLY DUE TO DUST-MOTES.—One of the most important results due to dust-motes is the diffusion of sunlight. If there were no dust or haze in suspension in the air, nothing would be visible except what received direct light or reflected rays from visible surfaces, and the optically pure[1] air occupying the space between illuminated objects would be practically dark. There would be no sky diffusion except for such of the shorter rays as might be scattered by the molecules of gases; and illumination, as one now understands it, would be impossible. The dust-motes receive light upon their many-sided surfaces, inclined to each other at nearly all conceivable angles, and then scatter or, if large enough, reflect[2] it in all directions, effecting the diffusion of light that illumines the air and also objects that are in the shade and not receiving direct light.

Prof. John Tyndall, in his researches on the decomposition of vapors by light, found it necessary to remove the dust-motes from the air used in his experiments, so that there should be nothing present to scatter the light. He demonstrated that the molecules of the air itself have not the property of diffusion[3] (see Chapter XIV); that air rendered dust-pure by passing it through highly heated platinum tubes and thereby destroying the floating particles by combustion, or air in which the dust-motes had been allowed to settle to the bottom of a closed and quiescent space, would leave the light rays invisible while passing through the transparent air.

Fig. 4 illustrates the passage of a ray of light through a tightly closed box, the air of which has become dust-free by remaining at rest for seven days. The front is of glass. The ray is seen as it passes from its source, at *l*, through the impure air to the window at *W*. It is again visible as it emerges from the box on the opposite side at *w* and reënters the dusty air of the outside; but across the interior space, where there are no dust-motes to scatter the ray, there is no illumination.

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[1] Free of even the minute dust-motes.

[2] Carefully read the paragraph in Chapter V that explains the difference between scattered and reflected light, pp. 49, 50.

[3] But Tyndall's conclusions do not agree with those reached by Rayleigh some years later, who was led to believe that the molecules of gases diffuse minute quantities of light which while unseen in the laboratory may become visible in large volumes of the free air.

Dust-free Air is Also Germ-free.—Many experiments have shown that air freed of dust-motes has at the same time been cleared of the microörganisms that cause fermentation, putrefaction, and disease; and that germ-free liquids or flesh may be indefinitely exposed in such air without fermentation or decay. Some time prior to 1869 Tyndall had demonstrated that air that has been filtered through the lungs has lost its power to scatter light, and is, therefore, germ-pure. The manner in which Tyndall demonstrated that the deeper portions of the lungs are filled with optically pure air is described as follows:

"Condensing in a dark room, and in dusty air, a powerful beam of light, and breathing through a glass tube (the tube actually employed was

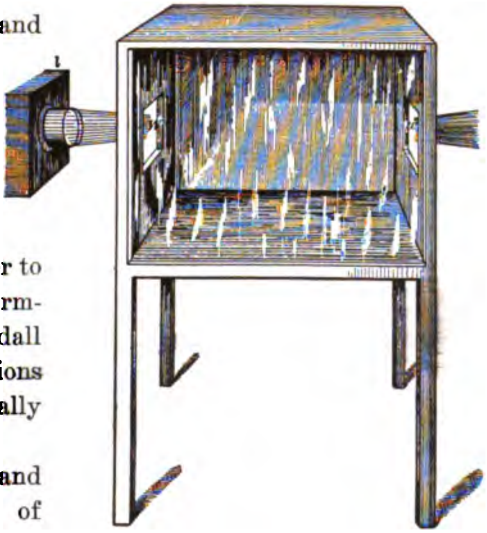

Fig. 4.—Shows Light to be Invisible while Passing Through Dust-pure Air.

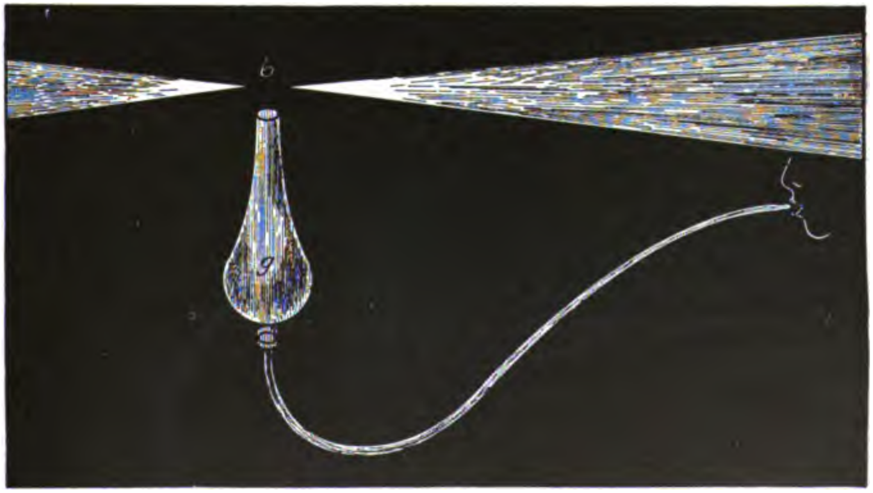

Fig. 5.—Optically Pure Air from the Lungs Renders Nonluminous a Ray of Light (Tyndall).

a lamp glass, rendered warm in a flame to prevent condensation of the breath) across the focus, a diminution of the scattered light was first observed. But toward the end of the expiration the white track of the beam was broken by a perfectly black gap, the blackness being due to the total absence from the expired air of any matter competent to scatter light. The experimental arrangement is represented in Fig. 5, where *g* represents the heated lamp glass, and *b* the black gap cut out of the beam at its brightest point."

Dust-motes Affect Twilight.—If it were not for dust-motes there would be a less brilliant and different twilight. The bending or refraction of light, as the sun's rays pass obliquely from the ether, at sunrise, or at sunset, into the optically denser medium of the air, displaces the apparent position of the sun, elevating it by an amount about equal to its apparent diameter, so that one may still see it and directly receive its light when geometrically it is entirely below the horizon. A little later in the evening and its rays fall upon the upper air too obliquely to be bent down to the earth by refraction, but darkness does not yet ensue, for the rays are scattered by the molecules of gases and the dust-motes and sent downward from particle to particle, resulting in a soft shimmering light that almost imperceptibly fades away, and which in higher latitudes, because of the obliqueness there of the sun's path to the horizon, may last for hours.

Dust-motes Nuclei for Condensation.—Dust-motes furnish the " free surfaces " that seem to be necessary in the condensation of the particles that form fog, clouds, drops of rain, and flakes of snow. (See Chapter XII.) In the laboratory condensation in dust-free air may take place on ions.[1] To what extent, if any, such precipitation takes place in the free air is not known.

Dust and Cloud Particles Determine Color of Sky.—The sky may receive a little of its blue tint from the true color of oxygen, but the scattering of the short wave-lengths of light, those that correspond to the violet end of the solar spectrum, by the molecules of gases, and by the dust-motes that are so small and light as to float in the upper air, are responsible for the blue of the sky. The various tints of red that often present such beautiful aspects when mingled with the somber stratus or snow-white cumulus clouds near the horizon, at sunrise or at sunset, are caused by the decomposition of light by the cloud particles, or by the coarser dust that at times is carried by swiftly ascending currents into portions of the lower air, through which the sun's rays must pass obliquely in the morning and in the evening. These particles arrest most effectively the light of short wave-lengths, and permit in great measure that of long wave-lengths —that is, the yellow, the orange, and the red—to pass through. (See Chapter XIV.)

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[1] Electrons, and electrified atoms.

How Dust-motes are Counted.—Aitken has devised several systems of apparatus to count the dust-motes of the air. Fig. 6 shows his first dust-counter. The others are modifications of this one and do not essentially depart from its construction. It would seem to be impossible to count millions of dust particles in the small space of 1 cubic centimeter, and, therefore, the process that Mr. Aitken's ingenuity has devised, and that is really quite simple, will be described substantially in his own words:

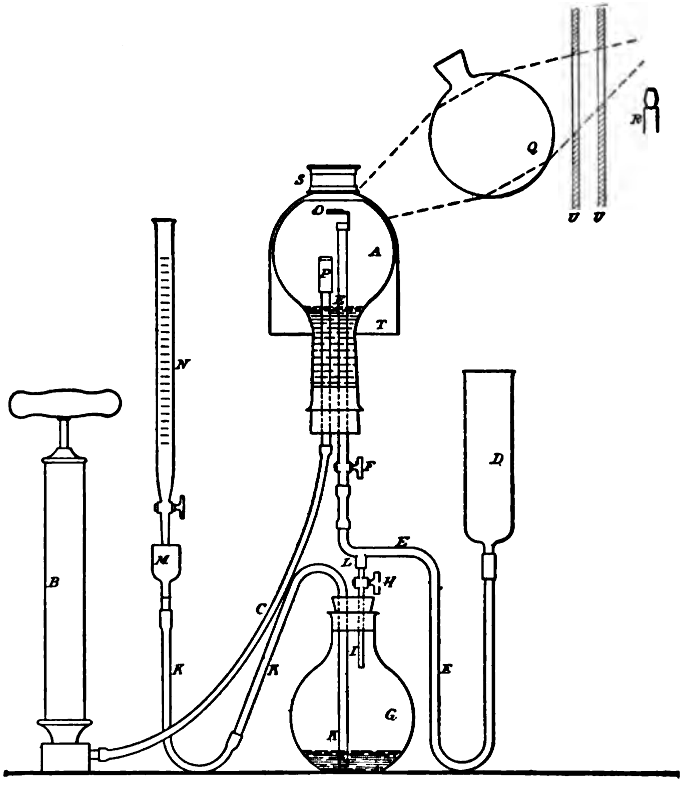

Fig. 6.—Dust-counter (Aitken).

"Having established the important fact that cloudy condensation in our atmosphere can only take place in the presence of dust;[1] that every cloud particle was previously represented in the atmosphere by a dust particle on which the vapor forming the cloud particle condensed, it seemed, therefore, probable that dust might play an important part in other meteorological phenomena, and if we could devise some way of estimating or counting the number of particles of dust in the atmosphere, that a new field of meteorological inquiry might be opened up, as it seemed probable that these small particles might play some unknown part in the economy of nature. Attempts have been made by others to collect dust in various ways, but none of them are suitable for giving the number of particles in the air tested, the object of previous investigators being to get the weight and composition of the dust falling in a given time. The experiments on cloudy condensation, however, suggested a method of counting them. Though many of the particles are too small to be seen with the highest powers of the microscope, yet it appeared to me that by making these extremely small particles, as well as larger ones, centers of condensation —that is, making them the nuclei of small rain drops—it might be easy to count the rain drops so formed and in this manner obtain the number of dust particles.

" When ordinary air is saturated and expanded the cloud is so dense that it seems as hopeless to attempt to count the different centers of condensation as to count the motes in a sunbeam. But we can make the number of dust particles—that is, centers of condensation—in a given volume of air as small as we wish by mixing a little dusty air with a large amount of dustless air, and we can allow the particles to fall on a micrometer and can count them by means of a lens or microscope. By simply allowing for the proportion of the dustless to the dusty air, and making the correct allowance for the dilution, we calculate the number of particles.

" The silver micrometer is highly polished in a particular way, and ruled into small squares of 1 millimeter. It is illuminated by means of a gas flame, the light being concentrated on it by means of a water lens, or ordinary daylight can be used. The drops are counted by means of an ordinary compound lens, no great magnifying power being necessary. Owing to the manner of polishing and of illuminating, the field appears black and on it the little drops shine out brightly and are easily counted.

" The apparatus by means of which the dust in the atmosphere was first counted is shown in Fig. 6. *A* is the receiver, an ordinary flat-bottomed flask, in which the air to be tested is cooled by expansion, and the number of drops is counted. The receiver *A* is connected with the air pump *B* by means of the india-rubber tube *C*, and with the filter *D* through the tube *E*. To saturate the air, some water is always kept in *A*. The drops are counted on the micrometer *O*, which is made of a plate of silver 1 centimeter square, highly polished, and ruled with lines at right angles to each other and 1 millimeter apart. It is illuminated by the gas flame *R*, the light being concentrated by means of the water lens *Q*. When the micrometer is in its place there is exactly 1 centimeter between its surface and the top of the receiver. The drops are counted by means of the lens *S*. To the pipe *E* is attached a branch *L*, by means of which the air to be tested is introduced into the receiver *A*. The stopcock *F* is opened and *H* is closed, after which the air pump is worked until all the impure air is removed from the receiver and its place taken with dustless air from the filter. After a short time the stopcock *F* is closed and a stroke of the pump made. This expands the air in *A*, and if there are any dust particles in it a shower of rain will be seen falling on the micrometer, on looking through the lens *S*. If any drops fall, more filtered air must be admitted, expansion made, and if still some drops fall, the process must be repeated until the drops cease falling, which will take place when the air is perfectly free from dust.

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[1] And possibly ions.—AUTHOR.

" The apparatus is now in a condition for making a test. To do this the flask *G* is disconnected from *L*, and filled with water. It is then taken to the place, the air of which we wish to test; the water is then emptied out and its place taken by the air. The stopper is then tightly replaced and the flask brought back and again connected with the apparatus. Any impure air that may have entered the apparatus when *G* was disconnected is got rid of and a test made in the following way: Suppose that 1 c.c. of the air to be tested be the correct amount to be mixed with the pure air in the receiver *A*; then 1 c.c. of water is allowed to run out of the burette *N* into the cup *M*, the level of the water in *M* having been previously brought to the engraved line on the exit tube. After 1 c.c. of water has been measured into *M* the stopcock *H* is opened and the measured quantity of water allowed to enter *G*. When the water in *M* falls to the engraved line, *H* is closed. By this means a cubic centimeter of air is displaced from *G* and sent into the tube *E*. Before this measuring process was done the stopcock *F* was closed and a stroke of the pump made, so that immediately after the measuring was done and the stopcock *H* closed, the stopcock *F* is opened, when, as there is a partial vacuum in the receiver *A*, the 1 c.c. of dusty air is drawn into *A* along with a quantity of filtered air. After the air has had time to get saturated, *F* is closed and a stroke of the pump is made, the micrometer being observed while the air is being expanded and the number of drops counted on some selected squares. A number of tests are made in this way, from which the average number of drops per square millimeter is obtained. From the number so obtained the number in the air tested is calculated. If there be 1 centimeter of air above the micrometer, then we must multiply the average number counted per square millimeter by 100 and that will give the number per cubic centimeter in the air in the receiver. This number then must be multiplied by the proportion of pure to impure air, and also by the proportion by which the air is expanded by the pump. When this is done we get the number in the air tested. It is not necessary to use always 1 c.c. of air to be tested, but less can hardly be used with any degree of accuracy with this apparatus. The amount should be such as to give not more than 5 drops per square millimeter. If more dust particles be present than give this number, we cannot be certain that all of them have become centers of condensation and have been counted; for when the particles are numerous all do not become active at once, but after the first particles have fallen the remaining ones may be seen if a second expansion be made.

"The method of working above described is only suitable for air that is not very impure, and when we can mix one or a number of cubic centimeters of it with the air in the receiver. For very impure air another plan was adopted. A small gasometer was filled with filtered air, and to this was added a measured quantity of the impure air; the two were then mixed. The filter *D* and tube *E* having been removed from the apparatus, the gasometer was connected with the apparatus at the stopcock *F*. The air from the gasometer was then allowed to flow through the receiver *A* till it had displaced all the air in it at the time. The stopcock *F* was then closed,

TABLE VI.

Number of Dust Particles in the Air.

SOURCE OF AIR.	Number per c.c.	Number per Cubic Inch.
Outside (raining)	32,000	521,000
Outside (fair)	130,000	2,119,000
Room	1,860,000	30,318,000
Room near ceiling	5,420,000	88,346,000
Bunsen flame	30,000,000	489,000,000

expansion made, the number of drops counted, and the calculation made as before. The table on page 36 gives the results of some tests made with this apparatus.

" These numbers are, of course, very variable, owing to changing conditions, but the figures obtained with the newer forms of apparatus do not differ greatly from these. Although we were prepared to find that, if the number of dust-motes in a sunbeam should ever be counted, the number would be very great, yet I imagine to most of us the above figures are almost a revelation, as the visible dust-motes do not amount to more than a small fraction of these numbers. The figures show that some of the dust particles must be inconceivably small, almost molecular in their dimensions. Millions in a cubic centimeter, and yet so light that their united mass cannot be weighed, and almost none of them visible with the highest powers of the microscope, and yet, for the reasons already given, these very small particles of matter are not gaseous."

BIBLIOGRAPHY

BEBBER, W. J. VAN, "Hygienische Meteorologie," Stuttgart, 1895.

Memoirs by HENRY DE VARIGNY, F. A. R. RUSSELL, and J. B. COHEN, in *Annual Report of the Smithsonian Institution*, 1895, pp. 135–386.

AITKEN, J., Papers in *Transactions Royal Society of Edinburgh*, vols. xxxv, xxxvii, xxxix, and *Proceedings Royal Society of Edinburgh*, vols. xvi, xvii, xx.

"Report of the International Meteorological Congress, held at Chicago, Ill., August 21–24, 1894," published as *Weather Bureau Bulletin No. 11*, Washington, 1894, 1895, 1896.

BARUS, CARL, "Report on the Condensation of Atmospheric Moisture," Weather Bureau, *Bulletin No. 12*, Washington, 1895.

CHAPTER IV

PHYSICAL CONDITIONS OF THE SUN AND ITS RELATION TO THE EARTH'S ATMOSPHERE

Origin of the Sun and the Planets.—A modified form of Laplace's nebular hypothesis assumes that when the early nebula, which filled the space included, at least, within the orbit of the sun's remotest planet, and which was composed of dust, or gaseous particles, or of dust particles surrounded by gaseous envelopes, began to contract under the influence of its own gravity, it commenced a rotation about its common center. Contraction caused it to gain in temperature, and a reduction in the diameter of the rotating mass effected an increase in the velocity of rotation. This process continued until increasing centrifugal force just equaled the attraction of gravitation, when, with the minutest further gain in the velocity of rotation, the outer rim was abandoned—*not thrown off*. This rim continued to rotate for a time, as the rings of Saturn are still doing, when it broke up and gathered about a center of its own, but continued to pursue the same orbit as before its disruption. Thus was formed, according to the most generally accepted hypothesis, the first and outer planet of the solar system; and thus, it is fair to assume, was formed our moon from matter abandoned by the earth, and in similar manner were the satellites of all other planets fashioned. As the sun continued to contract through a long period of years—measured by tens of millions—it grew hotter, increased in velocity of rotation, and successively abandoned the matter that now forms the several planets and the numerous asteroids of its system.

Solar Heat: Past, Present, and Future.—Laplace's theory assumes that originally the early nebulæ were at a very high temperature and that the sun and its satellites were formed under conditions of great original heat. This part of his theory is not now generally accepted, as the conditions are better met by assuming that the heat was evolved as the result of the reduction of gaseous volume. The investigations of J. Homer Lane, of Washington, D. C., have assisted in giving one a clearer idea as to how cosmical heat became manifest. He showed, in 1870, that a sphere of perfect gas, contracting by its own gravity, and losing heat by radiation, *must grow hotter* until it becomes so dense that it ceases to be a perfect gas. The energy made available by shrinkage more than compensates for the loss of heat by radiation that caused the contraction. This is not so in the case of solid or liquid masses; they cool under the contraction due to their own gravity.

SUN WARMER THAN ORIGINAL NEBULA, BUT INCREASE IN TEMPERATURE ARRESTED.—It is, therefore, reasonable to assume that the sun is now at a much higher temperature than was the nebula that first gave to it form; and that its increase of temperature was arrested a considerable time ago by its condensation into liquid, such as the drops that are supposed to constitute at least a part of the clouds of the photosphere. The present proportion of true gases and liquids is such as to maintain a constant, or nearly constant, condition of heat, which state of affairs will probably continue for many millions of years; how long no one knows. Helmholtz has shown that it requires a decrease of only 250 feet in the diameter of the sun to account for its annual output of heat. Newcomb estimates that, at the present rate of radiation, the sun will have shrunk to one half its present diameter in five million years, at which time it must contain such a proportion of liquid or solid that it can no longer maintain a constant temperature. He concludes that in ten million years it will have cooled to the extent of destroying life on the earth.

TEMPERATURE OF THE SUN'S SURFACE.—The effective temperature, or the temperature that a sheet of lampblack must have in order to radiate the amount of heat given off by the sun, has been estimated at from 10,000° to 15,000° F.; but the temperature is not uniformly or equally distributed over its surface, or through the matter and gases that compose the sun. It is believed to be hotter at the poles than at the equator. Joseph Henry's thermo-electric pile and Langley's bolometer, by delicate measurements of temperature, have shown that the centers of the sun spots are cooler than their outer rims, or than the adjacent regions, and that the total radiation of the sun, which has generally been assumed to be constant, may vary slightly from day to day and from year to year. It would seem reasonable to expect that for any given area there should be variations of an appreciable amount due to the thermodynamics of its gaseous and semigaseous parts, somewhat as sudden changes in temperature occur in the atmosphere of the earth, without necessarily assuming that there is any considerable variation in the total radiation for the whole surface.

It is believed that within the period of authentic history the average amount of the total heat received from the sun has remained practically unchanged, even though it be proved that there have been times of excess and of deficiency. In the long stretches of time that constitute geologic periods slow and persistent changes of climate have occurred on the earth, as shown by the carboniferous and the ice ages, but these are not ascribed to variations in the heat of the sun, and a satisfactory explanation of them is still sought.

TEMPERATURE OF SUN'S INTERIOR.—The interior of the sun near the surface is doubtless a very dense, hot gas. The pressure near the center has been calculated to be 5,000,000 pounds per square inch, and the temperature under this enormous weight at 1,000,000° F. We can form no idea as to the state of matter under such extraordinary conditions, except to assume that it must be held in a solid form and constitute a rigid nucleus, about which the gaseous envelopes rotate eastward at velocities that lag behind the central mass, the lag, or retardation, at the surface increasing with latitude in both hemispheres.

SOURCE OF THE SUN'S HEAT.—The falling into the sun of meteoric masses, or the combustion of its own matter, is far from being sufficient to account for the amount and intensity of its heat. If combustion were the source of its energy it would have been consumed long ago, and the impact of meteors would cause only a minute fraction of its heat. One is, therefore, led to accept the theory of contraction as well accounting for the sun's heat and its continuance.

AMOUNT OF SOLAR RADIATION INTERCEPTED BY THE EARTH.—Fig. 7, showing the comparative size of the sun and the earth, permits one to comprehend at a glance what an infinitesimal part of the total solar radiation is intercepted by the earth. If a globe 2 feet in diameter were placed upon a plane, a small pea 430 feet away might fitly be used to represent the earth.

Young, in his "General Astronomy," makes some interesting comparisons to illustrate the quantity and the intensity of radiation at the surface of the sun, stating that:

"If the sun were frozen over completely to a depth of 50 feet, the heat emitted is sufficient to melt the whole shell in one minute of time; if an ice bridge could be formed from the earth to the sun by a column of ice 2¼ miles square at the base and extending across the whole 93,000,000 miles, and if by some means the whole of the solar radiation could be concentrated upon this column, it would be melted in one second of time, and in between seven and eight seconds more would be dissipated in vapor. To maintain such a development of heat by combustion would require the hourly burning of a layer of the best anthracite coal from 16 to 20 feet thick over the sun's entire surface—a ton for every square foot of surface. . . . At that rate the sun, if made of solid coal, would not last 6,000 years. . . . The amount of heat emitted in a minute by a square meter of the sun's surface is about 46,000 times as great as that received by a square meter at the earth. . . . This heat radiation at the surface of the sun amounts to over 1,000,000 calories[1] per square meter per minute, and is over 100,000 horse power per square meter continuously acting. . . . Taking the earth's surface as a whole, the energy received during a year aggregates about 60 mile-tons for every square foot. That is to say, the heat annually received on each square foot of the earth's surface, if employed in a perfect heat engine, would be able to hoist 60 tons to the height of a mile."

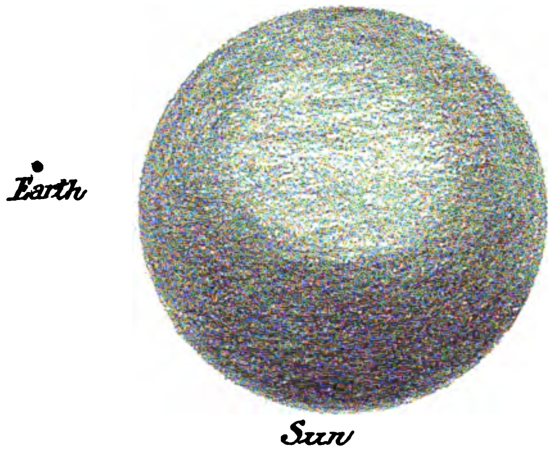

FIG. 7.—COMPARATIVE SIZE OF THE SUN AND THE EARTH
(BUT ON THIS SCALE THE DISTANCE APART SHOULD BE ABOUT TWENTY FEET.)

UNEQUAL RADIATION PROVES THE SUN HAS AN ATMOSPHERE.—Radiation, as measured from the earth, is greatest at the center of the solar disk, where the rays pass out nearly vertical through the least thickness of the sun's atmosphere, and least at the limb, where the rays are more oblique and where the amount of radiation is only about one half what it is at the center. This condition of unequal radiation from the center of the disk as compared with the limb proves the existence of an atmosphere.

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[1] A calorie is the amount of heat necessary to raise one kilogram of water 1° C.

Solar Day and Inclination of Sun's Axis.—It takes about twenty-seven of our days for the sun to complete one revolution on its axis, which has an inclination of only 7° 15′ from the normal to the ecliptic. The ecliptic is the plane of the earth's orbit. The inclination of the axis of the earth's rotation is 23° 30′ (about) from the normal to the ecliptic. If the earth's axis had no greater inclination than has the axis of the sun there would be but little variation in temperature between summer and winter, and there would be comparatively little difference in length between the shortest and the longest days.

Sun Spots, Faculæ, and Prominences.—These especially interest the meteorologist, since changes in their number, magnitude, and frequency are directly associated with the magnetic conditions of the earth, and possibly other terrestrial phenomena with which the meteorologist is intimately concerned.

Sun spots first begin to appear in the high latitudes of the sun—at 35° or 40°—and increase in number for some distance toward the equator. About five years from their minimum they will be in greatest number. About one half of the time none is visible. The periods of greatest frequency are about eleven years apart, the average intervals, which may range from eight to seventeen years, being almost exactly eleven years and forty-seven days. The time that a spot may remain in existence varies from a few days to two months. The center of a spot, called the *umbra,* is cooler and darker than the fringed border, called the *penumbra,* which is cooler and slightly darker than the photosphere. Some spots are so large that several bodies of the size of the earth would not fill the dark opening. The diameter of an umbra may range from 500 miles in the small spots to 50,000 miles in the large spots. The diameter of the penumbra may equal 150,000 miles. At times the centers are seen to be filled with downward-moving gases, radial filaments passing from the penumbra to the center and thence downward. They are always the centers of terrific cyclones and of strong magnetic fields. The faculæ are clouds that group themselves in the region of a spot. Unlike the spots, they are brighter than the photosphere. They take their name from the Latin word *facula* —a torch. The faculæ and spots are almost entirely confined to the region between latitudes 5° and 40°, north and south, and are most numerous between latitudes 10° and 20°. They have a slow movement. The prominences are formed of jets of highly heated hydrogen, which shoot upward through the vaporous clouds of the photosphere, at times, to heights of several hundred thousands of miles. The number seen on the edge of the disk of the sun from day to day has been counted for a long period. By

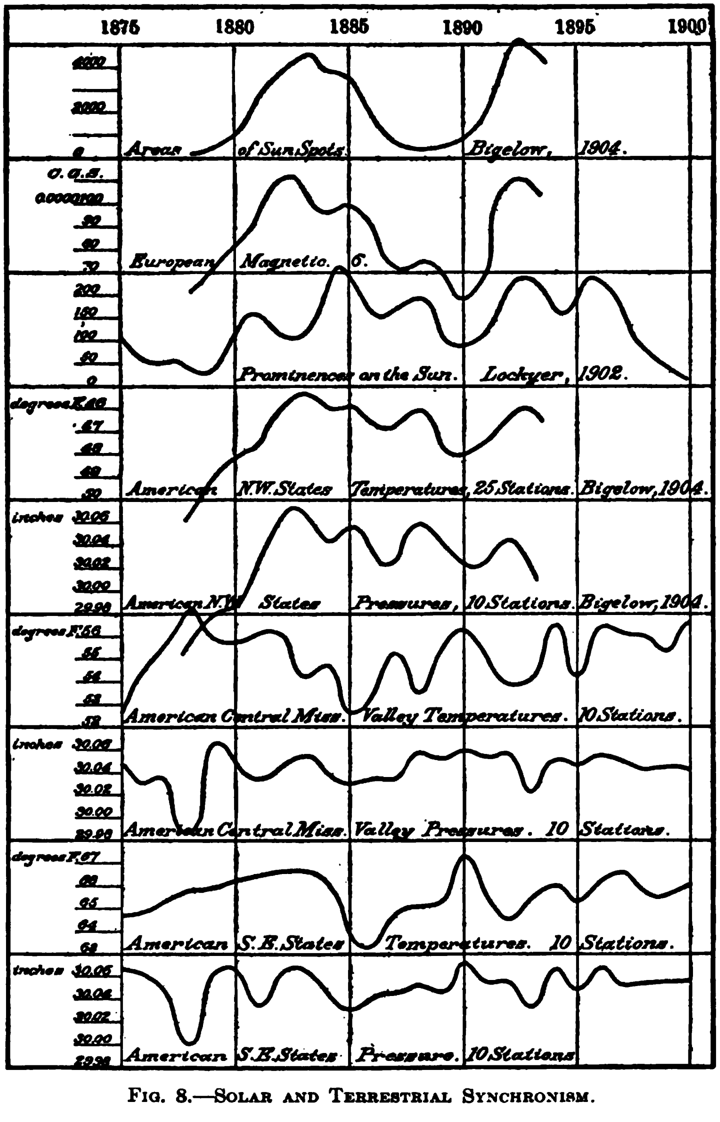

FIG. 8.—SOLAR AND TERRESTRIAL SYNCHRONISM.

an inspection of a thirty years' record they are known to vary in number largely from year to year. Similarly, the faculæ and spots, which have been studied for many years, have their fluctuations in cycles that are synchronous with the variations in the number of hydrogen flames.

Synchronism of Variations in Solar and Terrestrial Phenomena.—It is clearly shown that sun spots, faculæ, and prominences, and the earth's magnetism and auroral displays, vary with much the same rhythmic pulse, except that the spots are not as sensitive to changes in energy as are the other phenomena.

A study of the curves of Fig. 8 will show at a glance the close synchronism between the sun spots and the earth's magnetic force. There is, however, a variation, in periods of three or four years, in the magnetic curve, which does not appear in the spot curve; and this variation is still more pronounced in the prominence curve, which also shows a general trend with the spot curve. These three manifestations of activity seem, therefore, to be closely linked together.

When one attempts to fit together the remaining curves, representing terrestrial weather variations in the United States, with the magnetic or the solar curves, serious difficulties are encountered, for there seems to be little agreement of a direct form.

The Sun and the Weather.—So far the weight of opinion seems to be that the earth's weather and its variations are mainly functions of the mechanics of motion of the earth's lower atmosphere. In the *Monthly Weather Review* for June, 1901, p. 264, Prof. Cleveland Abbe writes:

"As the periodicities in sun spots, the width of the spectrum lines, the magnetic and auroral phenomena are sufficiently well marked to be satisfactorily demonstrable while the corresponding variations in pressure, temperature, wind, and rainfall are small, elusive, and debatable, we must caution our readers against being carried away by optimistic promises. It certainly is impressive to the thoughtful mind to realize that there is even a slight connection between solar and terrestrial phenomena, but the delicacy of this connection is such that it still remains true that the study of meteorology is essentially the study of the earth's atmosphere as acted upon by a constant source of heat, the sun. None of these astrophysical studies should tempt the meteorologist to wander far from the study of the dynamics of the earth's atmosphere and the effect of the oceans and continents that diversify the earth's surface."

BIBLIOGRAPHY

Lockyer, Sir J. Norman, "Simultaneous Solar and Terrestrial Changes," *Nature*, v. 69, 1904, pp. 351–357.

Hann, J., "Handbuch der Klimatologie," 3d ed., vol. i, Stuttgart, 1908, pp. 354 *et seq.*

Hann, J., "Handbook of Climatology," 2d ed., translated by R. DeC. Ward, New York, 1903, p. 404 *et seq.*

CHAPTER V

HEAT, LIGHT, AND TEMPERATURE

The Ether.—One cannot conceive of motion taking place in a void, for there would be nothing to move. Now heat, light, and other manifestations of energy come to the earth from the sun, and it is assumed that interstellar space must be filled by a transmitting medium, to which the name of *ether* has been given. It is not known whether this ether is continuous or molecular in structure, but it is believed that it penetrates all bodies and fills up the space between their molecules. One can only speculate as to its density and rigidity.

Solar Radiation.—The sun, with a diameter of 865,000 miles, which would fill the space occupied by our earth and also that inclosed by the orbit of our moon and extend 200,000 miles beyond, is continuously sending out an enormous quantity of radiant energy. Only a minute part of this encounters any planet and is absorbed, and thereby transmuted into other forms of energy. The greater part passes on indefinitely into space, becoming less and less intense with increasing distance. The amount received by the earth is but $\frac{1}{2200000000}$ part of the whole, yet in one minute it would heat 37,000,000,000 tons of water from the freezing to the boiling temperature, if 2.6 be the solar constant and 2,000 pounds the ton.

INSOLATION is the term applied to the solar radiation received by terrestrial or planetary objects. Formerly this word meant exposure to the sun's rays, and it is still occasionally used in that sense.

The change in temperature, in electrical state, in chemical composition, or any other effect produced on an object by exposure to sunshine, varies widely in nature and extent with different objects. In the case of black bodies, or perfect absorbers, essentially the entire effect is a change in temperature—a change that is measurable and directly proportional to the total incident energy.

Sunlight a Bundle of all Wave-lengths.—In a beam of sunlight a wide range of wave-lengths are found that were emitted at the same time from the same source. The structure of the luminous particle or atom, how it disturbs the ether and the process by which this disturbance is transmitted through the ether and communicated to material objects, are among the unsolved problems in physics. We know, however, that ether waves, however originated and of whatever wave-length, from the ultra-violet—the so-called actinic—to the ultra-red, and even to the long waves of wireless telegraphy, all obey the same laws of reflection, refraction,[1] polarization,[2] and interference,[3] and that in free ether they all have the same velocity of about 186,400 miles per second.

In the case of pure incandescence or black-body radiation, such as is emitted by lampblack, charcoal, etc., only long feeble waves are given out when heat is first applied. As the temperature rises more heat-waves are radiated, and if the temperature becomes high enough some invisible waves of shorter wave-lengths are sent out at the same time. If the substance be heated still hotter, it not only gives out all sorts of heat-waves, but visible rays representing every color from red to violet, and also ultra-violet waves, which are not visible—all mixed together.

Heat-waves do not Warm all Matter Equally.—It will be well now to consider what is the effect when heat-waves fall upon different kinds of matter. Let us take a glass filled with boiling water. You see the glass and the water because they reflect to the eye light-waves received from some source—possibly the sunlight that is diffused by the dust-motes of the air into the room through the window. If the room be darkened, one may feel with the nerves of the hand what the eye fails to perceive—namely, the long calorific or heat-waves. These waves are capable of warming all matter upon which they fall. But they do not warm all of the matter equally. The waves that reach dark and black bodies are broken up; that is to say, absorbed. Their energy is transmuted into sensible heat, and in place of the waves themselves we now have molecular vibrations in the matter, which are made manifest by a rise in its temperature. Rough dark surfaces more completely decompose the waves, and therefore rise to a higher temperature than the same surfaces when smooth. The effect is quite different when the waves encounter bright and highly polished surfaces; then most of them are reflected, and warm the matter but little. In this case the waves are not broken up, but, on the contrary, start off again in some new direction. The higher the polish the more completely are the waves reflected.

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[1] Bending out of a direct course.

[2] Restriction to vibration in one plane, transverse to the direction of the ray. Unpolarized light vibrates in all directions transversely to direction of propagation.

[3] Combinations of one ray with another in such manner as to diminish or increase its intensity.

Rays of Greatest Heating Effect.—The waves of greatest heating effect depend upon the natures and temperatures of the heating and the heated bodies; that is, upon the radiation of the one and upon the absorption of the other. In the case of the sun and a black body—one that completely absorbs radiations of all wave-lengths—the greatest heating effect is accomplished by the blue waves.

Waves of Light and Heat Minute as Compared to Sound.—As compared with the pulsations of compression and rarefaction that constitute the *sound-waves* of the air, light-waves and heat-waves are infinitesimal ripples, the sound-waves having lengths varying from 4½ feet for the middle *C* of the pianoforte to about 1 foot for those of the shrill notes of the human voice, or to only about one half inch for those of a shrill whistle; while a space 1 inch long contains about 22,000 of certain heat-waves of the invisible spectrum, over 30,000 of the longest waves of visible light (the red), and 66,000 of the shortest waves that affect the sense of sight (the violet).

Neither is the period[1] of sound-waves at all comparable with that of light. The human ear responds to sound-waves whose frequency is anything from 20 to 38,000 per second; while the eye is, roughly speaking, sensitive to light-waves of 500,000,000 millions to 1,000,000,000 millions per second. There are extremes of sound that to many ears are not appreciable, some being better adjusted to the low vibrations and some to the high. Tyndall could hear the shrill chirp of thousands of insects that were inaudible to his guide as the two climbed the Alps, but the guide's ears responded to the long, slow waves that came from the dull tread of a donkey's hoofs farther up the mountain, which waves were inaudible to the scientist. Similarly, some eyes appear to have unusual ranges, seeing far into the violet, or the red, or both; but the range is never great and probably chiefly, if not wholly, one of general acuteness of vision, or ability to detect feeble light whatever its wave-length. Again, many people distinguish notes of different pitch which to others sound exactly alike; and this, too, has its visual analogue, for some eyes cannot distinguish between certain colors. Persons possessing such eyes are said to be color-blind; usually it is the green and the red of equal tints or shades that look alike to them.

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[1] Time of vibration.

THE CHEMICAL ACTIVITIES OF LIGHT.—Actinic or photographic rays are found beyond the violet, having still shorter waves. They are sometimes called ultra-violet rays. Acting upon particular kinds of matter, they cause fluorescence[1] visible to the eye. They produce special physiological effects in vegetable and animal tissues. The chemical activities of light are not due entirely to this invisible portion; some of the visible rays, especially the blue and the violet, produce chemical changes. In most cases, however, other things being equal, the greatest actinic effect is caused by waves of 16½ millionths, or about $\frac{1}{60000}$ of an inch in length; these are shorter than any to which the nerve structures of our eyes are sensitive, while waves of 22 millionths present the greatest luminosity to the sight.

The chemical changes effected by light should not be regarded as wholly the work of the absorbed rays. Prof. William M. Davis, in his "Elementary Meteorology," paragraph 32, says:

"Substances thus affected may be regarded as so many springs, bent by previous chemical reactions into constrained positions, from which they would gladly free themselves if they could but make a beginning. The excitement caused among the molecules by the absorption of sunshine, or by radiant energy from any other sufficient source, merely releases the springs; and the consequent rearrangement of composition is the work of chemical attractions thus allowed to operate."

If the action is such as to produce heat, a start is all that is needed; if, on the other hand, heat is absorbed, then to maintain action energy must constantly be supplied.

REFLECTED AND SCATTERED LIGHT.—When nonpolarized light is incident upon a flat surface whose area is large in comparison to the square of the wave-length, a greater or less proportion of it is reflected according to the laws that:

1. The incident ray, the normal to the surface at the point of incidence, and the reflected ray, all lie in a common plane.

2. The angle between the incident ray and the normal to the surface at the point of incidence, the angle of incidence, is equal to the angle be-

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[1] The property possessed by some bodies of giving off, when illuminated, light of a color different from their own and from that of the incident light.

tween this normal and the reflected ray—that is, to the angle of reflection. Reflected light, of whatever wave-length, has a single definite direction as determined by the above laws. None can go straight forward, though all may be reflected directly back.

When, however, nonpolarized light falls upon an obstacle, no matter what its nature, whose volume is small in comparison to the cube of the wave-length, then there is no such thing as an angle of incidence for the light-wave as a whole, nor is the light that leaves this particle confined to any definite direction. A portion of the incident light goes on in the same direction that it came, while the rest of it is scattered and largely polarized. The intensity of the scattered light, according to Lord Rayleigh, is greatest backward, just half that amount in every direction at right angles to the incident ray, approximating zero straight forward, and of intermediate values at other points. When other things are equal the amount of the scattered portion of the light varies inversely as the fourth power of the wave-length.

POLARIZED LIGHT is secured by selecting from an ordinary beam of light only such waves as vibrate in one definite plane, and rejecting all others. Light from a flame, an electric lamp, the sun, or any other source, is nonpolarized.

Transfer of Solar Energy.—The transference of solar energy is accomplished by *radiation* and *reflection.* Radiation has been described in the beginning of this chapter. Reflection is the throwing off from the surface of a body of all or a part of whatever form of radiation falls upon it. The angle of incidence is always equal to the angle of reflection. For all except the ultra-violet, burnished silver is the best reflector known. It reflects 98 per cent of the visible and infra-red rays that fall upon it. In other words, it absorbs only 2 per cent of the heat-waves, the other 98 per cent departing with their energy undiminished. A good reflector, when once heated, is slow to lose its heat by radiation. Snow, water, and clouds are excellent reflectors. Much of the insolation that reaches their surfaces is sent back into space without warming them. Atmospheric air, entirely free of dust, fog, and vapor of water, reflects no heat.

Transference of Heat.[1]—The transference of heat is effected in other ways besides radiation and reflection.

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[1] For tables showing the coefficients of conductivity, and the specific heat of solids, of liquids, and of gases; and the latent heat of vaporization of liquids, the latent heat of melting of solids, the melting point of solids, the pressure of water vapor at various temperatures,

CONDUCTION is the communication of heat from the warmer to the colder places in an unevenly heated body, the heat being slowly passed from molecule to molecule. All matter does not conduct with equal facility; metals are the best conductors, silver leading the list, with copper second. Near the foot of the list of solids are snow and ice and mineral substances and organic materials, especially those in the fibrous or porous state, such as asbestos, wood, magnesia, brick, horn, leather, fiber, sand, cotton, wool, felt, and down. Such poor conductors are called *insulators.* It is important also to note that air and water are poor conductors. Organic material woven so as to contain numerous fine pores constitutes a good insulator. The feathers of birds and the fur of animals are excellent protectors against loss of heat because they contain numerous interstices filled with air.

CONVECTION is the distribution of heat by the movement of the warm body itself from places of higher to places of lower temperature, such as that which takes place in air or water when it is not homogeneously heated. When air comes in contact with a hot stove it is heated beyond the temperature of the air not in contact with the stove; it expands, its specific gravity is reduced, and it is forced to rise by the colder and heavier air surrounding it. The air that is first heated passes along the ceiling to colder parts of the room, gradually parting with its heat until it is no warmer than the air next adjacent to it, and slowly settling to the floor as the cold air beneath it moves toward the stove, is warmed and sent aloft, the first air finally making a complete circuit and returning to the stove again. In this way the heat from the stove is distributed by convection through the whole room, the circulation becoming the less active as the average temperature of the air in the room increases and reduces the difference between its own temperature and that of the stove. A similar action takes place on a large scale when one part of the earth's surface becomes hotter than another. The region of greater heat warms the air above it, and the surrounding denser air flows in along the surface, forcing the lighter air to rise, when it in turn is similarly warmed and driven up, and this process continues so long as the supply of heat and its distribution is sufficient to maintain the requisite differences in temperature. Wind consists of convection currents in the atmosphere.

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the boiling point of liquids, and the critical temperatures and pressures of gases, see the excellent article on heat in the "Encyclopedia Americana," by Prof. Ernest R. von Nardroff, E.M., D.Sc., head of science department, Erasmus High School, Brooklyn, N. Y.

DIATHERMANCY is that property of a body by which it transmits radiant heat without absorption. Rock salt is one of the best of all solid transmitters of long heat-waves. The gases of the atmosphere are also exceedingly good. The clear waters of lakes and rivers and of the ocean permit the passage of solar heat-waves to a considerable depth; but each layer absorbs a little of the energy, so that at a depth of a few hundred fathoms the absorption becomes complete. Window glass of a certain composition may screen off a considerable part of the heat-waves without seriously interfering with the transmission of light.

TRANSPARENCY is that property of a body that enables it to transmit light. Optically pure air is almost perfectly transparent, but the free air of nature, with its suspended moisture and dust, absorbs most of the minutest wave-lengths in and above the blue, and also many of the other parts of the spectrum. Ordinary window glass is transparent to but little more than the visual rays.

Specific Heat.—If equal masses of water and of mercury, at equal temperatures, be so placed as to receive equal quantities of heat in a given time, it will be found that the water will require nearly thirty minutes to reach the temperature that the mercury will attain in one minute. Water, which has a great capacity for heat, being taken as the standard, and the quantity of heat necessary to change a given weight of it by 1°, called unity, then the heat necessary to change the same weight of mercury through the same range of temperature is 0.034, which is its *specific heat.* The specific heat of ice is 0.502, which is greater than that of any other solid, except paraffin and wood, which are represented by the figures 0.694 and 0.6 respectively. With but few exceptions the specific heats of liquids are much greater than those of solids or gases. In the case of gases the specific heat is greater if the gas is allowed to expand so as to keep it at a constant pressure, the excess of specific heat being due almost entirely to the heat employed in doing the work against external pressure that is necessary in the process of expansion. At constant pressure, therefore, a less quantity of heat needs to be employed to raise the temperature of the gas by a given number of degrees, and we express the fact by saying that its specific heat is less. As the specific heat of water varies slightly with the temperature, it is well to take as the value of the gram-calorie $\frac{1}{100}$ of the heat required to raise the temperature of a gram of water from 0° C. to 100° C.

Latent Heat.—Temperature depends upon the energy of motion (kinetic energy) of the molecules of matter; latent heat *stores up* energy of position (potential energy) of the molecules, heat being employed in overcoming the attractive force of cohesion and not in increasing temperature. When a solid is melted or a liquid vaporized a large amount of heat energy becomes latent. As an illustration, we will take a pound of ice at 0° F. temperature. It requires the application of 16 heat units (see above) to raise this pound of ice to the temperature of melting (32° F.); and then it requires the application of 144 more heat units to so far overcome cohesion that the molecules may roll the one about the other in the liquid form, but with this important difference: The 144 units become latent and do not, therefore, cause any increase in temperature; this considerable quantity of heat is called the *latent heat of melting.* After the melting is complete any further addition of heat causes an increase in temperature, and 180 heat units will raise it to the boiling point. At sea level and normal air pressure water boils at 212° F.—that is to say, at that temperature the agitation of the molecules of water is so great as to overcome both cohesion and external pressure and cause them to fly away. But the entire pound of water is not instantly changed to the gaseous condition, for with the sending off of the first few molecules considerable heat is rendered latent, and more heat must be supplied or the ebullition ceases. Now the point is made that after the pound of water is brought to the boiling point it requires the application of 964.62 heat units to entirely change it to steam, but at no time does the temperature rise above 212°; this great amount of heat becomes latent; it is called the *latent heat of vaporization.*

It is well to note that the work done by the latent heat of vaporization in pushing back the atmosphere is only a little more than one twelfth of that done in increasing the internal potential energy of the molecules.

Cooling by Evaporation.—A liquid does not need to be raised in temperature to its boiling point before vaporization begins, for it operates at all temperatures, even after the liquid is frozen. At the surface some of the fastest-moving molecules are continually finding opportunity to escape from the attraction of cohesion—more from the liquid than from the frozen substance. As the temperature of a body is only a measure of the average kinetic energy[1] of its molecules, whether in the gaseous, the liquid, or the solid state, it follows that the escape of some of the faster-moving molecules results in a lowering of the average speed of those that remain, and consequently a decrease in temperature. The molecules that escape fly against the pull of cohesion and have their velocities lowered, and likewise their temperatures reduced. Thus does evaporation produce a cooling effect both upon the water left behind and upon the vapor that rises from it.

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[1] Mass times square of velocity.

Melting Point.—When a solid that expands on melting—as most solids do—is subjected to a considerable increase in pressure the action of liquefaction is resisted and a temperature slightly higher than that at which it ordinarily melts is necessary before melting begins. An increase of 100 atmospheres raises the melting point of paraffin from 115.3° F. (46.3° C.) to 121.8° F. (49.9° C.). On the contrary, pressure aids the process of melting in ice—a substance that contracts in melting—the melting point being lowered 0.013° F. (0.0072° C.) by an addition of one atmosphere to the pressure. The sharp edge of a skate, when applied to the ice under the weight of one's body, is lubricated by the slight melting of the molecules of ice in immediate contact with the skate, the molecules returning to the solid form as soon as the pressure is relieved. A wire may be slowly passed through a large block of ice, without leaving the block severed into two pieces, by attaching heavy weights to the two ends of the wire and suspending it across the ice, the ice melting as the result of the pressure applied by the underside of the wire and freezing molecules closing the space on top of the wire. This process of thawing and freezing is called regelation; it is one way of accounting for the moving of glaciers down tortuous valleys as though they were viscous masses.

Boiling Point.—Boiling begins in water, as in other volatile liquids, when its temperature is raised so high that the pressure of its saturated vapor equals the pressure of the air; then evaporation takes place in the interior of the liquid, as well as on its surface, and bubbles of vapor rise and pass off; while evaporation is at a less rate and only takes place from the surface so long as the temperature is below the boiling point. The temperature of boiling of an exposed liquid depends upon the atmospheric pressure. Thus, for water, the boiling point is 212° F. at sea level and ordinary air pressure; under a pressure of two atmospheres the boiling point is raised to about 250° F. The passage of severe winter storms may change the pressure so as to cause the boiling point at sea level to vary between 207° and 215° F.

THE MEASURING OF ALTITUDES BY THE BOILING POINT OF WATER.—The decrease of pressure with altitude lowers the boiling point, the amount being approximately 1° F. for each 555 feet of ascent. This knowledge is made use of in the measuring of the height of mountains, although the method does not give very close results. In its practical application the boiling point is observed as closely as possible with a thermometer graduated into many subdivisions of each degree. The difference between the temperature at which the water boils and 212° F. is then multiplied by the constant factor 555, and the product is the desired estimate of the elevation above the level of the sea. In this process it is assumed that at the time of observation on the mountain the atmospheric pressure at sea level has its average value, so that water would boil there at precisely 212° F. This favorable condition will seldom occur, but the departure from it will be the least during the summer months. It is well to take the average of estimates made on several different days.

Specific Heat of Air.—The amount of heat required to raise a given weight of dry air 1° in temperature, at a constant pressure, is 0.24 of the amount necessary to raise an equal weight of water 1°. This ratio is called the specific heat of air. The great capacity of water vapor for heat is indicated by its specific heat, which is just twice that of dry air; namely, 0.48. When the volume remains constant the amount of heat required to change the temperature of air is less than it is when free to expand, in the ratio of 1 to 1.41. This is due to the expenditure of heat in doing the work of pushing back the surrounding air.

Adiabatic Changes in Temperature.—Dry air cools by expansion in ascending at the rate of about 0.55 of a degree Fahrenheit for every 100 feet of elevation. In the same ratio it warms with descent. Heat, or molecular energy, is neither lost nor gained in this process. Such a change of temperature, as the result of changes of pressure, without the addition or subtraction of heat, is called an adiabatic process. If air at a temperature of 60° F. and a pressure of 30 inches have its pressure doubled, its volume diminishes to one half and its temperature rises to 175.5°, the first increase of pressure of 1 inch effecting an increase in temperature of 5°. If its pressure be diminished one half, its volume will expand to double the original size and its temperature will fall from 60° to 2.4°.

Absolute zero of temperature means the total absence of sensible heat. This hypothetical condition of coldness is approximately represented on the absolute Centigrade scale by 273.1° below the freezing point of water, and on the Fahrenheit scale by 459° below zero.

Natural Zero.—In a gas thermometer with which temperature is determined by the change in pressure of a mass of gas restricted to a constant volume, natural zero is the temperature at which there would cease to be any pressure whatever, if the same law of expansion held good at exceedingly low temperatures that obtains between the freezing and the boiling points of water.

If temperature be determined by the change in volume of a given mass of gas, confined under a constant pressure, then the natural zero would be the temperature at which the volume of gas would entirely disappear, if the ratio of contraction with falling temperature that prevails between the freezing and the boiling points of water held good down to the lowest extremity of the thermal scale.

The absolute and the natural zeros occupy almost precisely the same position on the scales of the various gas thermometers in use. They represent practically the same place reached by two different routes of travel; or the same conclusions led up to by different lines of experimentation and reasoning, one verifying the other.

Heat and Temperature not Synonymous.—The molecular agitation set up in a substance by the absorption of heat is indicated by the temperature, which gives no measure of the quantity of heat absorbed, the quantity varying widely for different kinds of matter.

HEAT UNIT.—In commercial use the amount of heat necessary to raise 1 pound of water 1° F. is the heat unit most generally employed; but in scientific literature the amount necessary to raise 1 gram of water 1° C. is the unit of heat (gram-calorie) best adapted to use.

Thermal Condition of Interstellar Space.—Although the ether transmits through all space the various forms of solar energy, none of this energy becomes thermal until it is intercepted by the atmosphere of our earth or by the gaseous envelope of some other planet, or by the body of some meteor or comet, or by cosmic dust. Objects, or planets without atmospheres, deep in interstellar space, are, therefore, nearly devoid of temperature, approaching absolute zero, which, theoretically, is $-459°$ F.

Solar Constant.—The number of gram-calories received per minute on a square centimeter of normal surface outside the earth's atmosphere is called the solar constant. The determinations of its value by different investigators, and even by the same investigator at different times, differ widely, depending upon the apparatus and the methods employed.

Many long series of measurements have failed to show a variation in the solar constant. Langley, however, with an improved form of the bolometer, found in his later work that the solar constant varies from time to time. Mr. C. G. Abbot, who for several years was Mr. Langley's aid, and after the death of the latter became Director of the Astrophysical Observatory of the Smithsonian Institution, conducted expeditions to Mt. Wilson, near Pasadena, Cal., during the summers of 1905, 1906, and 1908.

In the dry air of that region, with his observing camp located about one mile above sea level, where the general atmospheric absorption was only one half what it is at sea level, he obtained values of the solar constant varying from 1.93 to 2.14, the mean for the first two years being 2.022.

Bolometric Measurements.—The bolometer, or *actinic balance,* was devised in 1880 by Professor Langley for the purpose of measuring the distribution of heat in the solar spectrum. It consists of two strips of platinum foil, each about 10 mm. long, 0.1 mm. wide, and 0.002 mm. thick, blackened on the front and bright on the back. They are placed side by side so as to be under as nearly as possible identical conditions, except that the front of either may be exposed to the radiation to be measured, while the other is shaded therefrom.

As the exposed strip thus becomes heated its electrical resistance increases. Through a Wheatstone bridge device, the bolometer strips constituting two arms of the bridge, the deflection of the needle of a very sensitive galvanometer is made to indicate this change in resistance. It may be recorded photographically by means of a beam of light reflected from a mirror attached to the galvanometer needle.

As now used by Abbot, this instrument is capable of indicating variations of temperature in the exposed strip of only 0.000001° C. But, in order to make sure that these temperature variations are due to fluctuations in the radiation that is being measured, it is necessary to carefully exclude all extraneous sources of heat. This is accomplished by inclosing the bolometer and the resistance coils forming the other arms of the bridge in an air-tight tube surrounded by a water jacket, the complete apparatus being set up in a double-walled room inside an outer room, the temperature of the latter being kept constant by a self-regulating heating apparatus in winter and refrigerating apparatus in summer.

By means of suitably arranged mirrors, and a spectroscope that is rotated at a known rate, heat rays of different wave-lengths can be successively brought to the bolometer. The difference in intensity of the heat energy in these rays varies the electrical resistance of the exposed bolometer strip, and destroys the balance of the Wheatstone bridge system. A registration of the oscillations of the galvanometer needle is effected photographically. The quantity of heat for any wave-length that reaches the surface of the earth varies inversely with the amount of atmosphere through which it passes. If a represents the coefficient of atmospheric transmission for a given wave-length, or the portion of its energy that reaches the earth's surface with the sun in the zenith, and m the depth of atmosphere through which the rays pass at the time of observation, the law of variation is expressed by a^m. Since m varies very closely with the secant of the zenith distance of the sun, observations at two different hours of the day, with the sun at different zenith distances, should enable one to compute what proportion of the solar radiation has been absorbed by the atmosphere. Since we are also able to measure the quantity absorbed by the apparatus, we are therefore able to construct curves showing what the relative intensity of radiation was for each wave-length of light before it suffered absorption by the atmosphere, and also before it suffered absorption by the apparatus.

The ratio of the areas inclosed between these two intensity curves and their corresponding base lines is assumed to be the ratio of the total radiation received in a unit time by a normal surface outside the earth's atmosphere and that received by a similar surface at the place of observation. By means of this ratio the rate at which solar radiation is being received outside the earth's atmosphere may be computed, provided we first measure the rate at which it is being received at the surface of the earth. This measurement is usually effected by means of the pyrheliometer or the actinometer.

The Ångström electric compensation pyrheliometer in use by the Weather Bureau is shown in Fig. 9. Essentially, it consists of two thin bands of blackened platinum foil, *A, B,* mounted in a tube in such a way that they may be separately exposed to or shielded from the sun. They are backed up by bands of copper foil, from which they are insulated by oiled silk. These copper bands are joined by a constantan wire, *c, c,* thus forming thermo-electric junctions, and in circuit with them is a delicate galvanometer, *C*. An electric current can be made to pass through either platinum band at will by means of the switch *L*.

If both the platinum bands are exposed to the sun's rays at the same time, they should be heated equally, and there would be no galvanometer deflection. Shade one band and expose the other, and the difference in temperature at the two thermo-electric junctions will generate a current which will deflect the galvanometer. A current from a battery can then be made to pass through the shaded platinum band, warming it and nullifying the thermo-electric current until the galvanometer comes back to its original reading. We then conclude that the two platinum bands are at the same temperature again, and an ammeter shows how much current is required to produce the same heating effect as is produced by the sun's

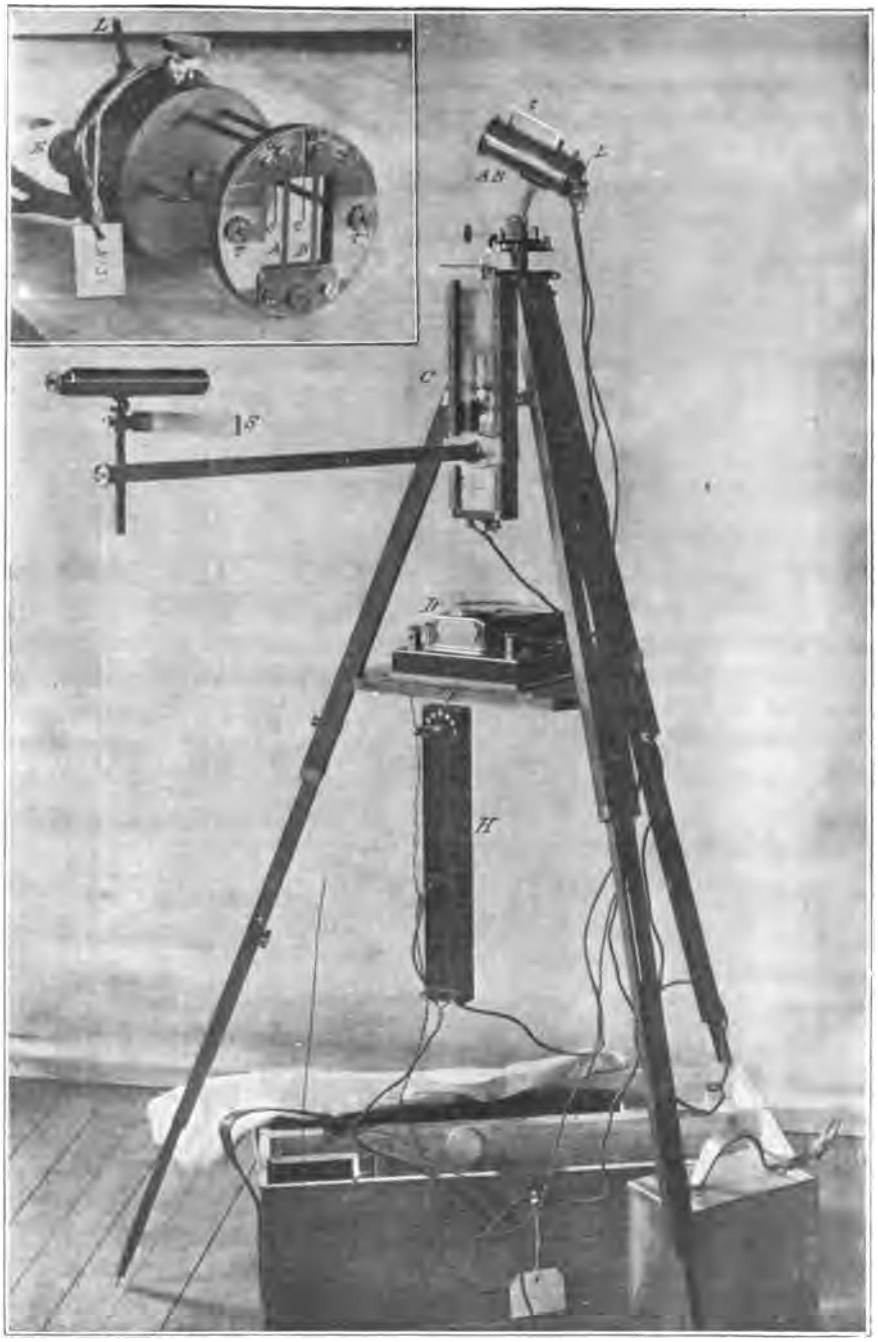

FIG. 9.—ÅNGSTRÖM'S ELECTRIC COMPENSATION PYRHELIOMETER.

rays. This current is a measure of the heat falling upon the exposed band, and is easily converted from ampères into heat units.

Actinometers are similar in principle to pyrheliometers, except that while the readings of the latter may be directly converted into heat units by means of the known constants of the instruments, the constants of the former are unknown, and comparative readings with a pyrheliometer are necessary before their indications can be reduced to heat units.

Observations with pyrheliometers and actinometers are subject to errors from several different sources that will not be here discussed.

BIBLIOGRAPHY

THOMPSON, SILVANUS P., "Light, Visible and Invisible," New York, etc., 1897.

MAXWELL, J. CLERK, "Theory of Heat," London, etc., 1902.

ÅNGSTRÖM, KNUT, "The Absolute Determination of the Radiation of Heat with the Electric Compensation Pyrheliometer," *Astrophysical Journal*, Chicago, v. 9, 1899, pp. 332–346.

SMITHSONIAN INSTITUTION, *Annals of the Astrophysical Observatory*, v. 2, Washington, 1908.

CHAPTER VI

THERMOMETRY[1]

Galileo's Water Thermometer.—Probably the first instrument for measuring temperature changes was constructed by Galileo at Padua, Italy, near the end of the sixteenth century. The principle employed by him was the same as that employed in the construction of modern thermometers —namely, the unequal expansion of gases, liquids, and metals with rise in temperature. Thus, Jena glass, mercury, and air expand 0.00002533, 0.0001818, and 0.00367 times their volumes at 0° C., respectively, for a rise in temperature of 1° C., or the cubical expansion of mercury is over 7 times, and the cubical expansion of air 145 times, that of glass. Galileo's thermometer was probably in the form of a large glass bulb with a long stem attached. The bulb was uppermost and the open end of the tube was immersed in a cup of water, with water also partly filling the stem. If then the temperature of the bulb was raised, the increased volume of the air that it contained depressed the column of water in the tube. Conversely, a decrease in the temperature of the bulb diminished the volume of air and allowed the water column to rise.

Mercurial Thermometer.—Similarly, when a glass bulb with a slender tube attached is filled with mercury, a rise in the temperature causes the mercury to overflow from the bulb into the tube, and the amount of this overflow is a measure of the rise in temperature. This is the form of Galileo's thermometer ordinarily used in measuring air temperature.

In order that the thermometer may respond quickly to changes in temperature it is necessary that the bulb be made as small as possible, and that it present as much surface as possible to the air. In the better grades of thermometers the bulb is therefore made cylindrical in form (Fig. 10) instead of spherical. The bore of the stem is made fine so that slight changes in the temperature of the bulb will cause a perceptible movement of mercury in the stem.

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[1] For a very complete history of the development, and discussion of the theory of thermometers, see "Treatise on Meteorological Apparatus and Methods," by Prof. Cleveland Abbe, *Annual Report of the Chief Signal Officer*, 1887, Part II.

In the construction of these thermometers, after the bulb and stem have been united they are filled with mercury, which is then boiled so as to expel all air and moisture. This is an important precaution, as air bubbles in the bulb introduce errors in the indications of the thermometer, and by adhering to the sides of the bore of the tube they interfere with the free movement of the mercurial column, in some cases even separating it into parts. The top end of the stem is sealed off when the temperature of the thermometer is high enough to completely fill the stem with mercury, thus excluding the air.

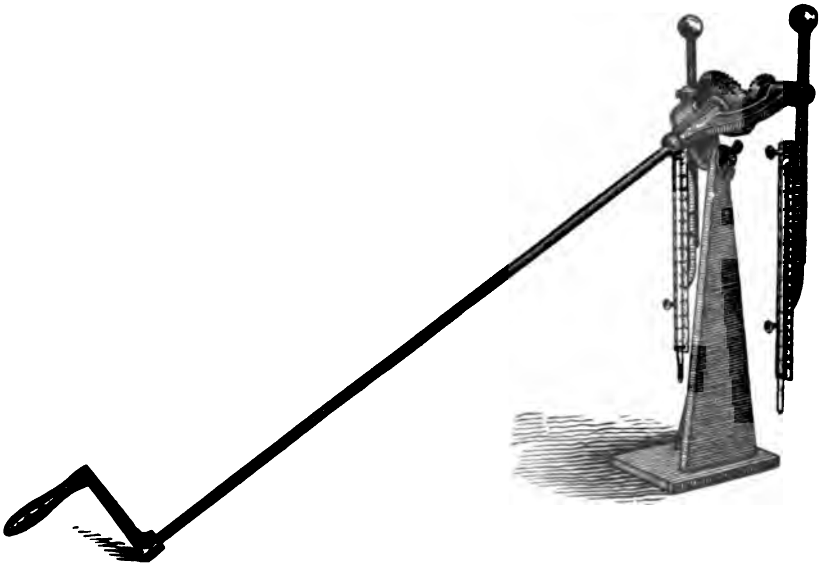

FIG. 10.—MERCURIAL THERMOMETERS, WEATHER BUREAU PATTERN, PRESENTED ON WHIRLING APPARATUS.

Unless a special kind of glass is used, the bulb of a thermometer becomes smaller with age. The instrument should therefore be laid aside for several months after it has been filled before the scale is etched on the glass.

Thermometer Scales.—The subdivisions on the early thermometer scales were quite arbitrary. One in Galileo's time was graduated from 0° to 360°, 0° representing the temperature of a mixture of ice and salt, and

360° that of the hottest summer day. This was an attempt to establish two fiducial points, and to divide the space between them into equal parts. Probably these equal parts were called degrees because of the fact that the stem of the thermometer was bent into the form of a complete circle. In nearly all the earlier thermometer scales, however, the divisions represented a fixed volume, it being erroneously supposed that the expansion was strictly proportional to the quantity of heat added, and that these divisions would therefore each indicate equal heat variations.

FAHRENHEIT'S EXPERIMENTS.—Fahrenheit, early in the eighteenth century, systematically investigated the subject of thermometer scales. On his first scale + 90° represented the temperature of the human body, and − 90° represented the temperature of an ice and salt mixture, the 180° of the scale, which was supposed to embrace all probable air temperatures, being equal in number to half the degrees in a circle. Later he adopted a scale on which 0° represented the greatest cold of the year 1709, and + 24° represented the temperature of the human body. The divisions on this scale were inconveniently large, and were therefore divided into fourths and renumbered, 96° representing the temperature of the human body.

Up to this point Fahrenheit had experimented with spirit thermometers. He now succeeded in making a mercurial thermometer, and with this verified experiments previously made by other investigators, showing that the temperature of boiling water is constant under constant pressure. Under normal air pressure he found this temperature to be 212° on his thermometer scale, and he adopted it as one of the fiducial points of his scale. The temperature of melting ice on this scale was 32°, and these two points were soon adopted by manufacturers as the fiducial points of the thermometer scale.

RÉAUMUR'S, CELSIUS'S, AND LINNÆUS'S EXPERIMENTS. — Réaumur found, as he thought, that 1,000 volumes of water at freezing temperature became 1,080 volumes at the boiling temperature. He therefore called the former 0° and the latter 80°. Celsius proposed a thermometer scale with 0° for the boiling point and 100° for the freezing point of water. Linnæus, the celebrated botanist, constructed thermometers on which the freezing point was marked 0° and the boiling point 100°. This scale, the Centigrade, is now in use throughout the world, except in English-speaking countries, where the Fahrenheit scale is still in general use, although the Réaumur scale is employed to a limited extent in some parts of Europe. Representing a temperature on these different scales by F, R, and C, respectively, the following equations will enable us to convert readings in one scale to either of the other scales:

$$
\begin{aligned}
C &= \tfrac{5}{9}(F-32);\\
C &= \tfrac{5}{4}R;\\
F &= \tfrac{9}{5}C+32;\\
F &= \tfrac{9}{4}R+32;\\
R &= \tfrac{4}{5}C;\\
R &= \tfrac{4}{9}(F-32).
\end{aligned}
$$

The Thermometric Standard.—As has already been stated, a mercurial thermometer whose subdivisions represent equal volumes will not correctly indicate temperature changes, on account of the changes in the coefficient of expansion of mercury with temperature. The coefficient of expansion of a perfect gas is independent of the temperature. Hydrogen gas acts very nearly as a perfect gas. If, therefore, we substitute hydrogen for mercury in our thermometer, and add a device for maintaining the gas at constant pressure, the changes in its volume will accurately indicate the temperature changes. It is found more convenient, however, to maintain the gas at constant volume, and measure temperature changes by the variation in its pressure. Since gas thermometers are quite elaborate, and complicated computations are involved in the reduction of the readings, it is customary to fix by comparison with the gas thermometer the points on mercurial thermometer scales representing every tenth or twentieth degree of temperature between the fiducial points. The space between these pointings may then be divided into equal parts without introducing serious errors in the scale. Thermometers thus pointed are used as standards for the comparison of other thermometers.

The scale errors of thermometers should be determined by comparison with a standard, and they should occasionally be packed in melting ice to ascertain if the position of the fiducial point has shifted on the scale.

Alcoholic Thermometers.—Since mercury freezes at a temperature of about $-40°$ F., thermometers filled with alcohol, which freezes at about $-180°$ F., are used for measuring very low temperatures. They are not so accurate as mercurial thermometers, as the alcohol is liable to adhere to the sides of the tube, particularly if the fall in temperature is rapid.

Registering Thermometers.—Probably the most important temperatures to determine are the maximum and the minimum of each day. A self-recording device is desirable for this purpose. In the case of maximum temperatures this is easily provided for by constricting the size of the bore of

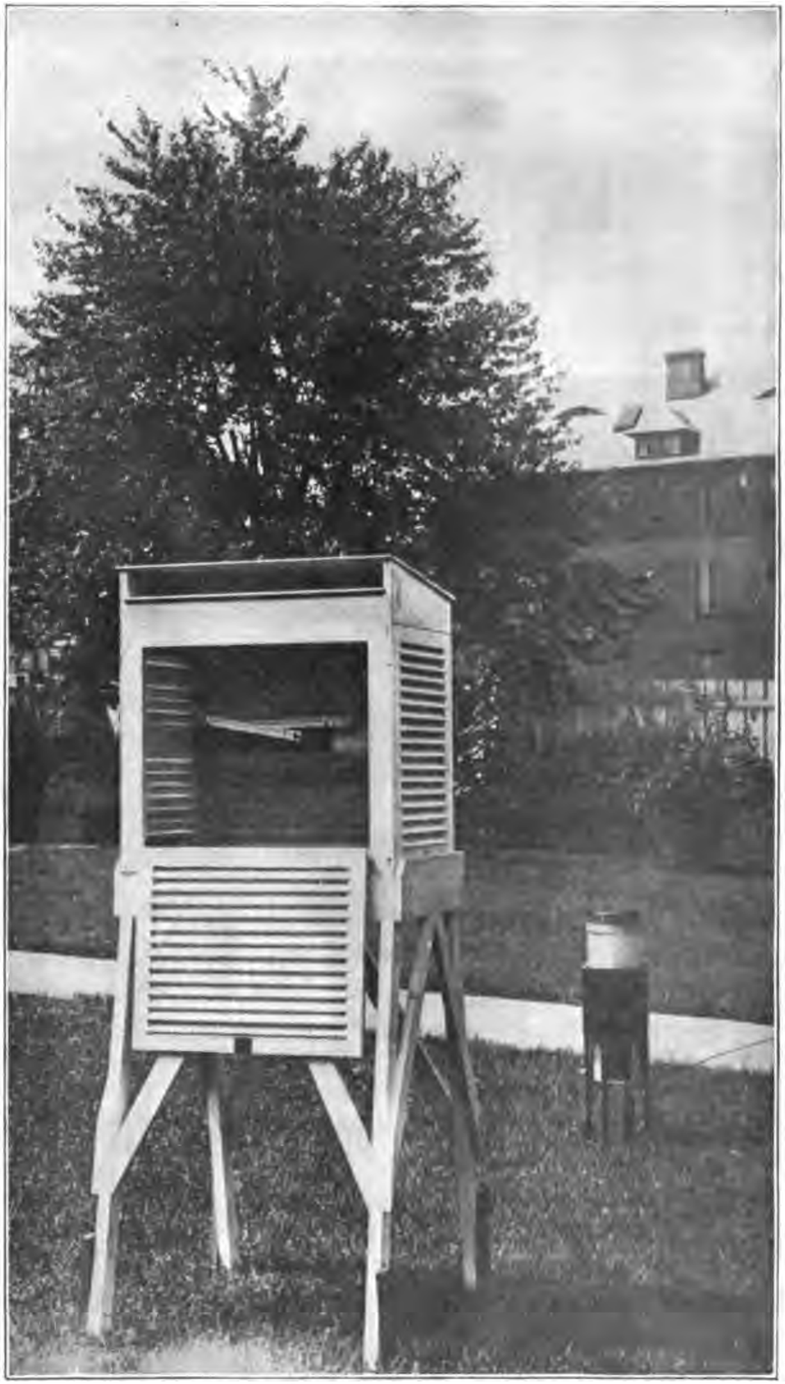

FIG. 11.—THERMOMETER SHELTER.

the tube just above the bulb by pressing in the sides of the tube while it is still soft from heating. The force of expansion will push the mercury up through this constriction when the temperature rises, but if the thermometer is supported horizontally, as shown in Fig. 11, there is nothing to cause the mercury to run back into the bulb when the temperature falls. The top of the column of mercury will therefore indicate the maximum temperature that has occurred since the thermometer was set. Maximum thermometers are usually set each morning by whirling the bulb end rapidly about a pin support near the upper end of the tube. If any considerable fall in temperature has occurred between the time of the registering of the maximum and the time of reading the thermometer, a slight error will be introduced due to the contraction in the length of the mercurial column.

For the registration of the minimum temperature an alcohol thermometer is usually employed, also supported horizontally. A small index of colored glass is immersed in the alcohol column. The surface tension at the top of the column is sufficient to prevent the penetration of the index and to pull it down when the temperature falls, but the liquid flows freely around the index and therefore there is nothing to carry it up again when the temperature rises. The position of the upper end of the index therefore indicates the lowest temperature that has occurred since the thermometer was set. The setting is accomplished by simply elevating the bulb end of the thermometer until the index slides down to contact with the top of the alcohol column.

Thermographs.—These are instruments for continuously recording the temperature of the atmosphere. One very common form is the Richard thermograph, shown in Fig. 12. A bent oval metal tube is filled with alcohol under slight pressure. Any rise in temperature will cause an increase in the internal pressure of the tube and will straighten it somewhat. A fall in temperature will diminish the internal pressure, and allow the tube to curl slightly. The free end of the tube is connected through a system of levers to a long arm carrying a pen, so that the pen traces on paper wound about a drum that is revolved by clockwork, a record, on a magnified scale, of the movements of the free end of the tube. The paper can be ruled so that the trace shall represent temperatures on any desired scale.

METAL THERMOMETERS.—Two thin ribbons of metal having unequal coefficients of expansion may be united on their broader surfaces and then wound in the shape of a coil. Temperature changes will cause this coil to wind or unwind, and this movement may be magnified and recorded as in the case of the Richard thermograph.

ELECTRICAL RESISTANCE THERMOMETERS, in which the variations in the electrical resistance of a wire are employed to measure the temperature, are advantageously employed for measuring small fluctuations in air temperatures, and also for measuring temperatures in inaccessible places, such as ground temperatures at considerable depths below the surface.

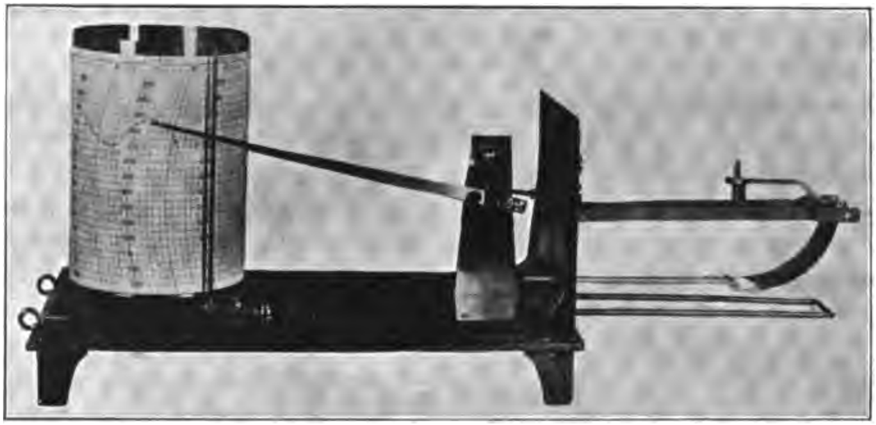

FIG. 12.—RICHARD THERMOGRAPH (CASE REMOVED).

In all forms of continuously recording thermometers, however, it is necessary to check the record frequently by comparison with the readings of an accurate mercurial thermometer.

Thermometer Exposure.—In order that thermometers may indicate the temperature of the free air it is necessary that they be exposed where they will not receive direct radiation from the sun or sky or from surrounding objects, and where the air can circulate freely. They also must be protected from rain and snow as far as possible. A thermometer shelter such as is shown in Fig. 11, if placed in an open space, probably affords the best exposure obtainable. In large cities it is necessary to locate the shelter on the roof of a building, if possible on one higher than any surrounding it, care being taken to avoid the influence of chimneys, skylights, ventilators, etc. Thermometers that are exposed to direct radiation from any source, even though they are protected from direct solar radiation, cannot indicate the true temperature of the air.

BIBLIOGRAPHY

ABBE, CLEVELAND, " Treatise on Meteorological Apparatus and Methods," Washington, 1888. (United States Signal Office, *Annual Report of the Chief Signal Officer for 1887,* Appendix 46.)

BOLTON, HENRY CARRINGTON, " Evolution of the Thermometer, 1592–1743," Easton, Pa., 1900.

CHAPTER VII

DISTRIBUTION OF INSOLATION AND THE RESULTING TEMPERATURES OF THE ATMOSPHERE, THE LAND, AND THE WATER

Source of the Earth's Heat.—It is generally held that the interior of the earth still retains an intensely high temperature, and that this hot mass is surrounded by a cool crust that is a poor conductor; so that only a small amount of heat escapes to the atmosphere. The innumerable stars, though their average temperature probably is equal to that of our sun, are too distant to have an appreciable effect in heating the exterior of the earth. It is apparent, therefore, that the sun, with an absolute temperature over twenty times as high as the absolute temperature of the surface of the earth, controls the surface temperature of our planet and its atmosphere.

Effect on Insolation of Inclination of Earth's Axis to Ecliptic, and Variation in Distance from Sun.—The quantity of heat that falls upon a horizontal area at the top of the earth's atmosphere during any consecutive twenty-four hours depends upon three conditions: (1) The altitude that the sun attains when it crosses the meridian at noon, (2) the length of the daytime, and (3) the distance of the earth from the sun; these are in a perpetual state of variation, except that near the equator the day and the night are always equal.[1]

Fig. 13 shows the course and the relative length of the diurnal arc, at latitude 45° N., at different seasons of the year. The distance from the sun varies because the orbit of the earth is an ellipse, with the sun in one of the foci. The time that the sun remains above the horizon, and the height it reaches at noon, change from day to day and from winter to summer, because the earth's axis is inclined at a nearly constant angle to the plane of its orbit, or the ecliptic. The extent of these changes is determined by the amount of this inclination, and is great because it is large—that is, 23.5° (Fig. 14).

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[1] In this statement no account is taken of the slight lengthening of daylight due to refraction.

If the earth's axis were vertical to the plane of its orbit it would always stand square to the rays of the sun and the northern and southern edges of the lighted surface of the earth would forever just touch the poles (Fig. 15). All places would have days and nights of twelve hours each, and the amount of heat received on the top of the atmosphere at any given locality, while proportional to the cosine of its latitude, would remain constant throughout the year; and all parts of any meridian would come into the sunlight at the same instant and enter darkness in a similar manner.

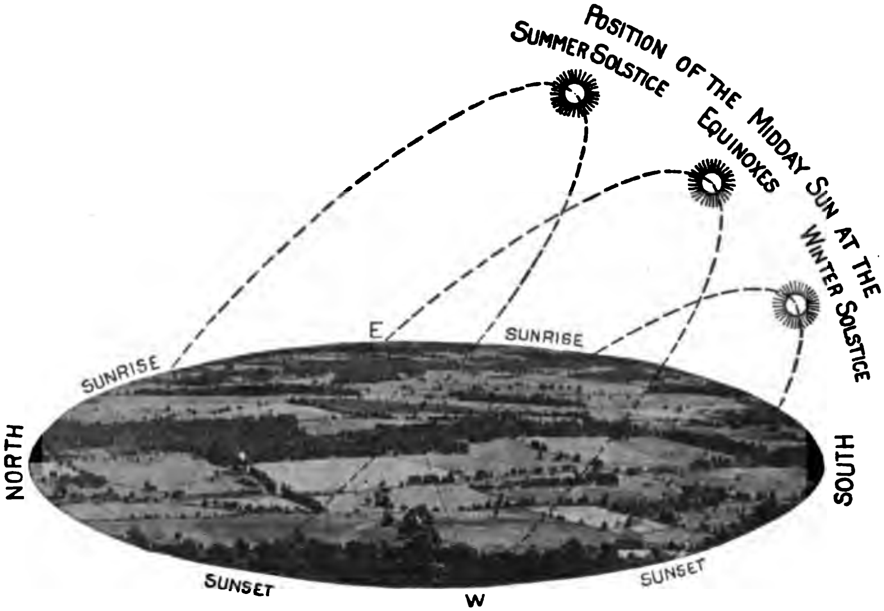


FIG. 13.—COURSE OF THE SUN AND RELATIVE LENGTH OF ITS DIURNAL ARC AT DIFFERENT SEASONS OF THE YEAR, FOR LATITUDE 45° NORTH, OBSERVER AT CENTER OF PICTURE.

From the *vernal equinox,* March 21st, the course of the earth in its orbit is such as gradually to change the relative position of the sun with regard to the inclination of the earth's axis, which latter maintains a fixed direction, until at the *summer solstice,* June 21st, the northern half of the axis leans toward the sun 23.5°, which is the greatest extent of its inclination, and the southern half leans away from the sun a like amount (Fig. 16). The effect is that the light shines 23.5° beyond the North Pole and fails to reach the South Pole by the same distance; it shines on more

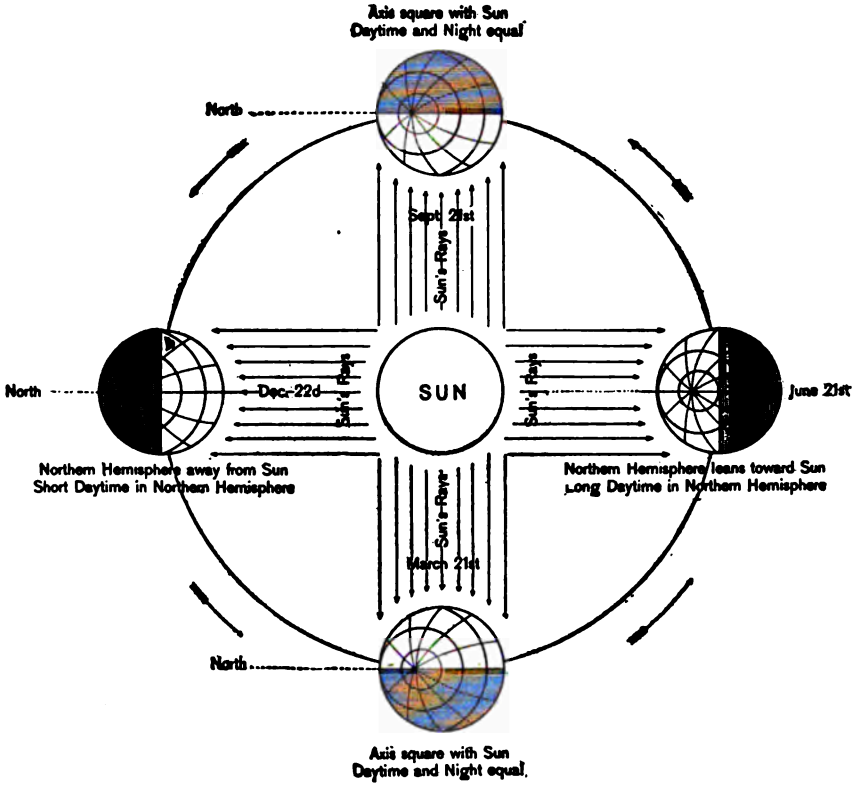
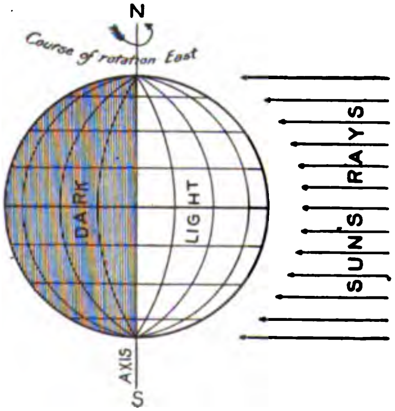


FIG. 14.—CAUSE OF SEASONS DUE TO SHIFTING OF ILLUMINATED HEMISPHERE WITH MOVEMENT OF EARTH IN ITS ORBIT, DIRECTION OF AXIS UNCHANGED.



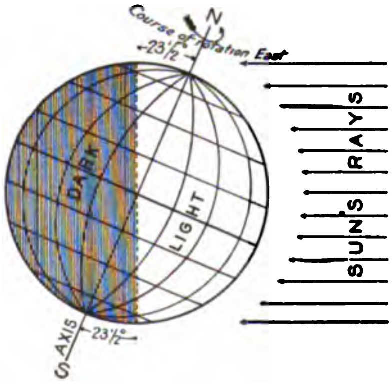


FIG. 15.—AXIS PERPENDICULAR TO SUN'S RAYS AS AT THE TWO EQUINOXES ON MARCH 21ST AND SEPTEMBER 22D.

FIG. 16.—NORTH POLE LEANING TOWARD SUN'S RAYS AS AT SUMMER SOLSTICE ON JUNE 21ST.

than half of each parallel north of the equator, while it covers less than half of each circle south of the equator. At the equator, as is always the case, half of the circle is lighted, and therefore the day and the night are equal. The farther north a point lies the greater is the lighted portion of the parallel that it follows in the earth's rotation, until a point is reached where the whole of the circle is in the light, and consequently the daylight is continuous. The point is 23.5° from the pole, and is on the *arctic circle.* No two places on the same meridian come into the daylight simultaneously as they would if the axis were vertical to the sun's rays. The first point south of the arctic circle comes into the light first as the earth rotates eastward and is the last to enter the darkness; the next point south meets the light a little later and leaves it a little earlier, and so on, each place coming into light later and leaving earlier, thus shortening the time that it receives heat, until at the equator this is reduced to only twelve hours. These variations in the length of daytime have an important climatic effect, as will be more fully brought out in subsequent pages, actually causing each frigid zone to receive a greater quantity of heat during any consecutive twenty-four hours of its midsummer than is received at the same time on a like area of the tropics, and this notwithstanding the more direct falling of the solar rays upon the latter.

South of the equator the daylight grows shorter and the night longer as points on the same meridian are selected farther and farther south, until the *antarctic circle* is reached, 23.5° from the South Pole, where the whole circle is in complete darkness and there is no daylight during the twenty-four hours, conditions just the reverse of those in the north frigid zone.

At the time now being considered, the summer solstice, there has been no night at the North Pole for about ninety-three days, nor will there be for about ninety-three days more. These two periods make a total of one hundred and eighty-six days of continuous sunshine, which goes far toward overcoming the intense cold caused by a similar period of darkness that occurs between the autumnal equinox on September 22d and the vernal equinox on March 21st; so that the average temperature of the air, at the surface of the earth, inside of the arctic circle, rises from 40° F. below zero in midwinter to 35° above in midsummer.

At the North Pole, from March 21st to June 21st, the motion of the sun, as it appears to the eye, is in a spiral around the horizon, ascending higher and higher and remaining in sight all the time. On June 21st it begins to descend in a similar spiral,. disappearing below the horizon at the *autumnal equinox,* on September 22d, and does not again appear for six months. The moment it disappears from view at the North Pole it appears at the South Pole and there sheds its oblique rays for the six months that it is absent from the North Pole. The greatest possible duration of sunshine at different latitudes, disregarding atmospheric refraction, is as follows:

LATITUDE.	Period of Visibility.	LATITUDE.	Period of Visibility.	LATITUDE.	Period of Visibility.
0°	12 hours.	63°	20 hours.	69° 51′	2 months.
17°	13 hours.	66.5°	24 hours.	78° 11′	4 months.
49°	16 hours.	67° 21′	1 month.	90°	6 months.

LIGHT ZONES.—At the two equinoxes the sun's rays at midday are vertical at the equator and touch each pole. The day and the night are everywhere equal, and the northern and southern hemispheres receive the same amounts of heat. At the summer solstice the northern hemisphere is turned most toward the sun and receives the most heat, the sun having reached its highest latitude and standing vertical over the parallel 23.5° north, which is the *Tropic of Cancer,* the northern boundary of the *Torrid Zone.* At this time the sun's rays fall short of reaching the South Pole by 23.5°; they cease at the *Antarctic Circle.* At the winter solstice (Fig. 17), on December 21st, when the southern hemisphere is turned most toward the sun and receives the most heat, the sun has reached the limit of its course, and at midday stands vertical over latitude 23.5° south, which is the *Tropic of Capricorn,* the southern boundary of the *Torrid Zone.* At this time the sun's rays fail to reach the North Pole by 23.5°; they cease at the *Arctic Circle.*

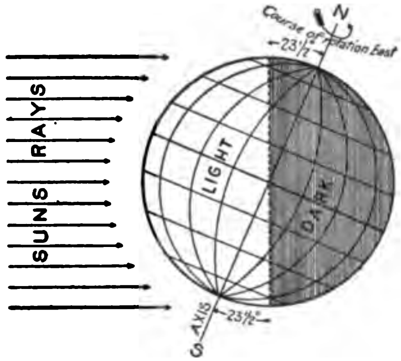


FIG. 17.—WINTER SOLSTICE, DECEMBER 21ST. North Pole leaning in same direction as at summer solstice, but earth being on other side of its orbit, sun's rays come from opposite direction and therefore North Pole is in darkness now and South Pole in light.

Periodic Variations in the Intensity of Insolation at a Given Place.—It will be well first to consider what would take place if we had insolation without an atmosphere; or, what is the same thing, if the atmosphere should permit solar radiation to reach the surface of the earth undiminished in quantity.

Hourly variations in insolation are due to the movement of the sun across the sky. Starting at sunrise, the horizontal plane *AB* (Fig. 18) located on the surface of the earth, receives a quantity of insolation that increases as the sun gains in height above the horizon. When the sun's rays pass along the lines *AA'*, *BB'*, they reach the surface at *AB* and are comprised within the cylinder *AA'*, *BB'*, whose right section *A'B'* increases as the direction *AA'* makes successively larger angles with the horizon, until the sun crosses the meridian at noon; after which it decreases until sunset. It is therefore plain that in the case of *A'B'* the quantity of insolation during the night is zero, and that it increases during the first half of the time of daylight and diminishes during the second half.

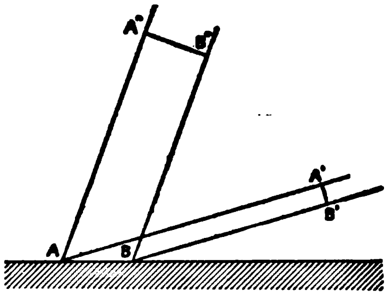


Fig. 18.—Intensity of Solar Radiation Varies with Altitude of Sun.

Difference Between Quantity and Intensity of Insolation.—Fig. 19 shows that as the angle of incidence increases a given quantity of insolation is distributed over a larger surface, and therefore its intensity diminished.

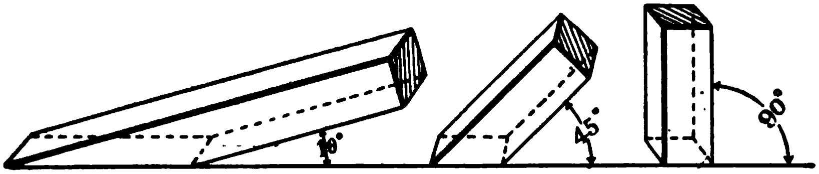


Fig. 19.—Varying Intensity of Insolation Under Different Angles of Incidence of Sun's Rays (Abbe, Jr.).

Daily Variations in Insolation.—We will first consider the course of events at the equator. Here the length of the daytime does not deviate from twelve hours throughout the year, and it is therefore necessary to take account only of the variations in the altitude of the sun above the horizon, and of its distance from the earth. The quantity of insolation received during each of the two days when the sun crosses the equator, March 21st and September 22d, is greater than the amount received on any other day of the year, for then the sun is precisely in the plane of the equator and passes through the zenith at noon, when its rays are vertical.

From the equinoxes to the solstices the insolation diminishes each day, for the sun each day fails to cross the meridian quite so near to the zenith as it did on the day preceding, causing a gradual gain in the obliquity of the rays. There is, therefore, a double annual oscillation in a curve representing the quantity of insolation received per day at the equator, with the maxima at the equinoxes and the minima at the solstices.

SEASONAL VARIATIONS IN INSOLATION.—But the amplitudes (Curve 1, Fig. 20) of these oscillations are not precisely equal, as they would be if the earth described a perfect circle about the sun instead of an ellipse, and were always at the same distance from it, since the insolation decreases as the square of the distance increases. A reference to the curve will show that the minimum of the winter solstice in December does not

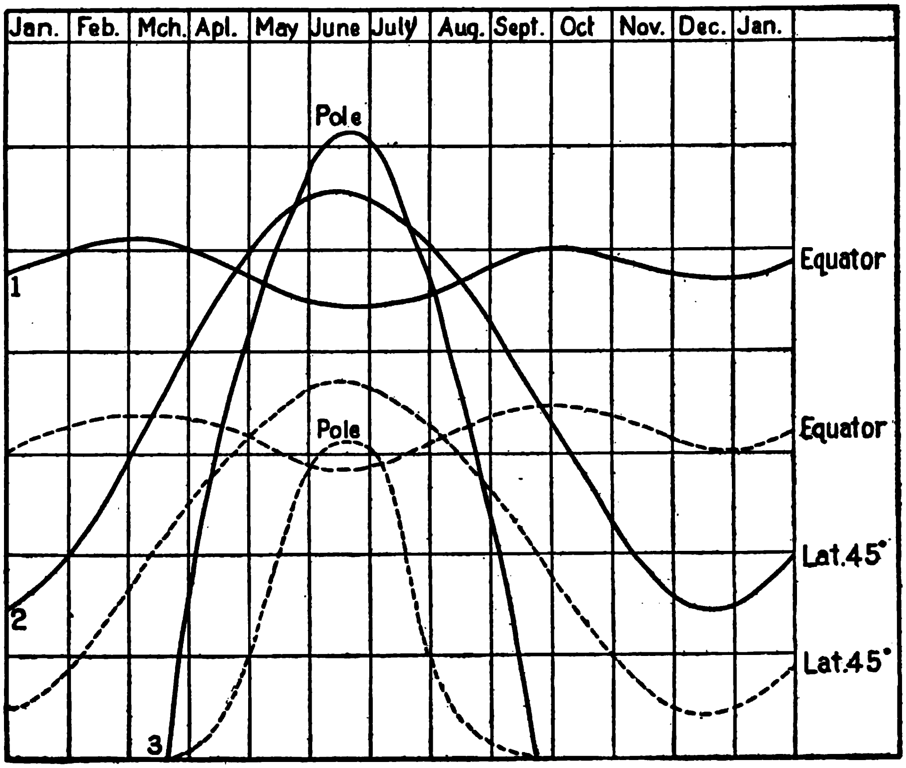


FIG. 20.—ANNUAL VARIATION IN THE AMOUNT OF SOLAR RADIATION (after Angot).

show such a deficiency in insolation as that of the summer solstice in June; the reason is made clear when we take into account the difference in the distance of the earth from the sun at perihelion (January 1st) and that at aphelion (July 2d), which is such that the insolation received is greater at the first epoch than at the second in the ratio of 107 to 100. In spite, however, of the inequality of the two oscillations, the total quantity received at the equator from the vernal to the autumnal equinox is exactly equal to that received from the autumnal to the vernal; for the ellipticity of the earth's orbit produces not only variations in the sun's distance but an inequality in the duration of the seasons. The longer period, 186 days, occurs between the vernal equinox and the autumnal, when the earth, because of its greater distance from the sun, moves at less than its normal rate of speed through one half of its orbit; the shorter period, 179 days, occurs between the autumnal equinox and the vernal, when the earth, because of its less distance from the sun and the consequent greater attraction between them, moves at more than its average rate. It can be demonstrated that the increase of insolation due to greater duration is precisely equal to its decrease caused by greater distance.

As points are selected farther and farther from the equator in the northern hemisphere, it is found that the December minimum of Curve 1 (Fig. 20) gradually deepens, while the June minimum fills up. The two maxima steadily approach each other until at and beyond latitude 23.5° they are merged into one. The curve now presents but a single maximum (summer) and a single minimum (winter). Curve 2 represents the well-marked conditions at latitude 45°. Here, from the winter to the summer solstice the insolation received steadily increases as the sun successively crosses the meridian at noon at a point a little nearer the zenith each day and remains longer above the horizon. During the other half of the year these conditions are reversed. There thus occur during the year at latitude 45° but a single maximum and a single minimum.

We will now transfer our investigations from latitude 45° north to the pole. The sun does not rise from September 22d to March 21st, and therefore the insolation received is zero. From March 21st to September 22d the sun is constantly above the horizon, its altitude at noon steadily increasing until June 21st, and decreasing after that date. The insolation received is represented by Curve 3 (Fig. 20), the maximum occurring near the time of the solstice, the same as at 45° north. On June 21st the altitude of the sun is 23° 27′ above the horizon, and it remains nearly constant at that altitude during the entire twenty-four hours, while at the equator the elevation of the sun varies from 0° at sunrise to 66° 33′ at noon, and the period of sunshine is twelve hours. The result is that the length of day at the pole more than compensates for the low altitude of the sun, and more solar energy falls upon the atmosphere of the latter place than upon the atmosphere of the equator, in the ratio of 136 to 100.

SOUTHERN HEMISPHERE HAS SHORTER SUMMER THAN NORTHERN, BUT AMOUNT OF INSOLATION EQUAL.—What has been said about the distribution of insolation on the northern hemisphere applies equally well to the southern by reversing the seasons, except that the effect of the variation in the earth's distance from the sun is reversed. In the case of the southern hemisphere, the earth is nearer to the sun in summer and farther away in winter, conditions that tend to add to the extremes of both seasons. At its winter solstice there is less insolation at any point of the southern hemisphere than at the corresponding point north at the summer solstice, but because of the slowness of the earth in passing through one half of its orbit, the northern summer lasts 93 days, while that of the southern hemisphere lasts but 89, with the result that during like seasons and during the whole year the two hemispheres receive exactly the same quantity of insolation.

INSOLATION MORE INTENSE AT POLES THAN AT EQUATOR DURING SUMMER.—The rapidly increasing length of the day toward the poles during summer soon more than compensates for the decreasing angle at which the solar rays strike the earth. This is shown by the following table (VII), which gives the proportional amount of insolation received in twenty-four hours at different latitudes and at different times of the year, the amount of insolation received at the equator on March 21st being taken as unity:

TABLE VII.

Proportional Amounts of Insolation. (Davis, modified.)

	LATITUDE.					
	0°	+ 20°	+ 40°	+ 60°	N. Pole. + 90°	S. Pole. − 90°
March 21st	1.000	0.934	0.763	0.499	0.000	0.000
June 21st	0.881	1.040	1.103	1.090	1.202	0.000
September 22d	0.984	0.938	0.760	0.499	0.000	0.000
December 21st	0.942	0.679	0.352	0.053	0.000	1.284

Such would be the distribution of insolation in the absence of an atmosphere. The large amount received at the pole may be unexpected.

Total Annual Insolation of Different Latitudes.—We will now sum up the insolation received at different latitudes during the entire year, and it should be remembered that the latitudes that have unusually long days in summer have equally long nights in winter. Table VIII, adopted from Hann, gives the total yearly insolation for every 5° of latitude, the unit being the amount that would be received at the equator in one day at the time of the equinox, if the sun were at its mean distance from the earth.

Table VIII.

Annual Amounts of Insolation.

Latitude.	Thermal Days.	Difference.	Latitude.	Thermal Days.	Difference.
0°	350.3		50°	239.6	19.1
5°	349.1	1.2	55°	219.4	20.2
10°	345.5	3.6	60°	199.2	20.2
15°	339.4	6.1	65°	180.2	19.0
20°	331.2	8.2	70°	166.2	14.0
25°	320.5	10.7	75°	156.5	9.7
30°	307.9	12.6	80°	150.2	6.3
35°	293.2	14.7	85°	146.5	3.7
40°	276.8	16.4	90°	145.4	1.1
45°	258.7	18.1			

Annually the pole receives 41 per cent of the amount of insolation that reaches the equator, while it would receive no insolation whatever if the axis of the earth were not inclined from the perpendicular to the plane of its orbit. The annual insolation varies but little with change of latitude near the equator and near the poles; the most rapid variation occurs between latitudes 50° and 60°.

Variations in the Quantity of Solar Energy Absorbed by the Atmosphere.—On the average the atmosphere of the earth absorbs about 76 per cent of the total incident solar energy. For a long time it was thought that it intercepted not over 30 per cent, but more recent researches—especially those by Abbot—indicate that about one half is absorbed by a cloudless atmosphere, and nearly all absorbed or reflected away by a cloudy air. On the average 52 per cent of the earth's surface is obscured by clouds all the time, which, according to Abbot, reduces the total amount of insolation that reaches the earth to but 24 per cent. In regions like the high plateau of the Rocky Mountains, where there is but little cloudiness or moisture in any form in the air, not over 50 per cent is absorbed.

The quantity of insolation absorbed by the earth's atmosphere varies with the hour of the day and with the season of the year, and with the amount of water vapor and clouds and other matter in suspension which affect its transparency.

Insolation that Reaches the Earth Decreases with Latitude.—When the sun is in the zenith at noon the rays strike the surface perpendicularly and reach the earth through the shortest air distance possible, but for latitudes far north or south of the equator, the rays are more oblique, and must pass through an ever-increasing thickness of air. Consequently, the insolation that reaches the earth at high latitudes decreases not only on account of the greater obliquity of the sun's rays toward the surface (Fig. 19), but also because of the longer path of atmosphere traversed, which causes a further loss by absorption and diffuse reflection.

Table IX.

Intensity of Insolation at Different Solar Altitudes.

Altitude of the Sun.	Relative Length of the Path of Rays through the Atmosphere.	Intensity of Insolation on a Surface Perpendicular to the Rays.	Intensity of Insolation on a Horizontal Surface.
0°	44.7	0.00	0.00
5°	10.8	0.15	0.01
10°	5.7	0.31	0.05
20°	2.92	0.51	0.17
30°	2.00	0.62	0.31
40°	1.56	0.68	0.44
50°	1.31	0.72	0.55
60°	1.15	0.75	0.65
70°	1.06	0.76	0.72
80°	1.02	0.77	0.76
90°	1.00	0.78	0.78

Coefficient of Transmission.—The fractional part of insolation that reaches the surface of the earth when the sun is in the zenith, and therefore after passing through a unit atmosphere, is called the coefficient of transmission or coefficient of transparency. According to Table IX, 78 per cent of insolation reaches the earth when the sun is vertical and the sky clear and the percentage of humidity low. All wave-lengths of radiation do not suffer equal absorption. With the sun in the zenith the general coefficient of transmission for wave-lengths at the red end of the spectrum is 0.8, and for the shorter waves at the violet end is 0.4; but water vapor and carbon dioxide, by specific absorption, completely cut off certain long wave-lengths, so that in general, except for the arid and semiarid regions of certain continental areas, the atmosphere transmits more freely the wave-lengths that are not extreme in length.

The law for absorption formulated by Bouguer is as follows:

For a given coefficient of transparency the quantities of heat transmitted decrease in geometric progression when the quantities of air traversed increase in arithmetic progression.

ANNUAL VARIATION IN THE ABSORPTION OF INSOLATION.—The annual variations of the quantities of insolation that would be transmitted to the surface of the earth through an atmosphere having a transparency of 0.75 are shown by the dotted curves of Fig. 20. These curves are analogous, so far as general outline is concerned, to those representing the total insolation. It will be noticed that the greatest absorption is in the polar regions, where the sun is always low on the horizon, and the oblique rays pass through the greatest quantity of air.

In calculating the annual distribution of insolation over the earth's surface we encounter a difficult problem. The general results found by Angot, assuming an average atmospheric transparency of 0.6, are presented by a table (Table X), which gives for each month and the year, and for every 20° of latitude from the equator to the pole, the calculated insolation that reaches the surface of the earth in mean equatorial days. The unit is the amount that the equator would receive in one day at the time of the equinox, with the sun at mean distance. In calories this unit is 458.4 multiplied by the solar constant; and assuming, as did Angot, the solar constant to be 3, his unit is 1375.2 gram-calories.

TABLE X.

Calculated Insolation Reaching Earth. (Angot.)

LAT.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Year.
N.													
90°	0.0	0.0	0.0	1.4	6.7	9.9	7.9	2.4	0.1	0.0	0.0	0.0	28.4
80°	0.0	0.0	0.2	2.7	7.5	10.3	8.5	3.8	0.5	0.0	0.0	0.0	33.5
60°	0.1	1.0	3.9	8.2	12.0	13.8	12.6	9.2	4.9	1.5	0.2	0.0	67.4
40°	3.3	5.7	9.4	12.9	15.3	16.2	15.6	13.5	10.2	6.6	3.8	2.7	115.2
20°	9.0	11.2	13.6	15.2	15.8	15.9	15.8	15.3	14.0	11.7	9.4	8.2	155.1
Equator	14.0	14.9	15.3	14.6	13.5	12.8	13.1	14.2	15.0	15.0	14.2	13.6	170.2
S.													
20°	16.8	15.9	13.9	11.2	8.8	7.7	8.3	10.5	13.1	15.3	16.6	17.0	155.1
40°	16.6	13.9	9.9	6.0	3.4	2.4	3.0	5.2	8.8	12.8	15.9	17.3	115.2
60°	13.4	9.2	4.4	1.3	0.1	0.0	0.1	0.8	3.4	7.8	12.3	14.6	67.4
80°	8.8	3.5	0.4	0.0	0.0	0.0	0.0	0.0	0.1	2.3	7.4	11.0	33.5
90°	8.3	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	6.5	10.5	28.4

Now it will be interesting to compare the annual totals from this table with the annual totals for a globe devoid of air, in order to get a clear idea of the effect of the atmosphere.

LATITUDE.	Without Atmosphere.	With Atmosphere. Transparency 0.6.
Equator	350.3	170.2
10°	345.5	166.5
20°	331.2	155.1
30°	307.9	137.6
40°	276.8	115.2
50°	239.6	90.6
60°	199.2	67.4
70°	166.2	47.4
80°	150.2	33.5
Pole	145.4	28.4

Therefore, theoretically, the atmosphere at the equator absorbs nearly one half the insolation, while it absorbs four fifths of the theoretical amount at the poles. In consequence of the varying degree of cloudiness of the sky, the amount actually absorbed is much greater than calculated, amounting, as stated at the opening of this chapter, to about 76 per cent.

Terrestrial Radiation.—When solar radiation is intercepted and absorbed either by the gases of the air or by dust in suspension in it, or by the earth itself, the energy of the ether is transmuted into molecular vibration of the matter that absorbed it. The temperature of the matter is raised and it itself sends out radiation in the form of *heat-waves*, which, like the greater part of solar radiation, readily escape through the atmosphere unless intercepted in their passage by cloud or water vapor. *The idea that the clear, dry atmosphere itself acts as a trap for the long waves of radiation that are convertible into heat—allowing them to enter but preventing their escape—is not now generally accepted.*

There is no permanent increase in the temperature of the earth or atmosphere, therefore there must be a continual loss of heat in some way, and this is brought about by the outward radiation of earth and air toward interplanetary space. About 5 per cent of the solar radiation is reflected from the surface particles of the ground without producing any warming effect upon them. Of the heat that is absorbed by the ground, about 40 per cent is carried into the solid earth by conduction; a large portion of this downward-moving heat is employed in the evaporation of soil water, and then, in the latent condition, passes upward to the air with the water vapor and is liberated when the vapor is condensed in the form of clouds, fogs, or dew; the rest continues downward and will be accounted for in the paragraph that treats of earth temperatures; another portion, about 10 per cent, is radiated from the surface and passes outward into space, unless intercepted by water vapor or clouds, since neither the atmosphere nor its dust absorbs more than a small portion of the energy in these long waves. The remaining 50 per cent is given up to the air by conduction from the warm surface of the earth, the air in immediate contact with the earth being crowded upward by the cooler and heavier air from above, which forces its way beneath it. During the spring and summer the gain of heat by the atmosphere is greater than the loss; during the autumn and winter these conditions are reversed.

WHY MOUNTAIN PEAKS ARE COLD.—The absorption of solar and of terrestrial radiation by the air is greater in its lower levels, where dust, water vapor, and cloud are densest, while the transmission of both incoming and outgoing radiation is more rapid through the purer air aloft. Thus we account for the coolness of all mountain peaks, and the perpetual freezing temperatures of some, even though they be located in the tropics, and though their tops occupy positions several miles nearer the sun than the bases from which they rise.

NOCTURNAL COOLING OF EARTH AND AIR.—Terrestrial radiation goes on day and night, winter and summer. During daylight the gain of heat is greater than the loss, while at night the reverse is true. After the sun has passed below the horizon both the earth and the air continue to cool by radiation unretarded by the counteracting effect of insolation. The earth loses heat, even under a clear sky, more freely than the air, with the result that the surface of the ground and of vegetation, and the air in close proximity thereto, may sink to a temperature 10° to 15° lower than that of the air at considerable elevations. This condition is called *temperature inversion*. It occurs both summer and winter. The greater difference will occur when there is but little wind to mix the air. When the temperature of the earth falls below the temperature of the adjacent air, there is a movement of heat both by conduction and by radiation from this air to the earth, as well as to the colder regions above. On a clear night in summer the radiation outward will be rapid; then, if but little wind be blowing, there will occur an increase in temperature up to a height of from 200 to 600 feet, and then a steady fall, reaching the surface temperature at about 2,000 feet elevation, unless radiation from the soil be diminished by saturation, or the location be adjacent to a large body of water.

A covering of cloud, fog, or dense haze may not only screen off the heat of day, but greatly retard the lowering of temperature at night by reflecting and radiating back to the ground the heat that it loses.

The difference between the outward terrestrial radiation of twenty-four hours and the insolation received during sunlight may be judged by measurements made in Finland in 1896 by Prof. Th. Homén. On the 14th and 15th of August the total heat received was 349 calories (average), and the loss by night 115; leaving a remainder effective in warming the surface of 234 calories. On the 2d and 3d of September the difference was 231 calories, and on the 1st and 2d of October only 50 calories.

The Temperature of Rivers, Lakes, and Oceans.—The facility with which matter radiates heat of a given wave-length is in proportion to its power of absorption of heat of this same wave-length. But the thermal effect of a given quantity of heat falling upon various forms of matter differs with the substance; this is notably apparent when the matter is land, water, or air. The same amount of heat will raise the temperature of a water surface only about one fourth as much as it will raise the temperature of a land surface. Water rejects by reflection a considerable amount of the solar radiation that reaches it, while land reflects but a small part, and of that that falls upon the top layer of water much is rendered latent in the process of evaporation, and does not impart warmth to the water. Solar radiation also penetrates water to a considerable depth and is quite uniformly absorbed by the whole stratum penetrated. These conditions give to large water surfaces, and the air immediately over them, a much lower temperature during the day and a much higher temperature during the night, and also lower temperatures during summer and higher temperatures during winter, than occur over a land surface of the same latitude.

COMPARATIVE THERMAL CONDITIONS OF FRESH AND OF SALT WATER.—The specific heat of sea water is less than that of fresh water, in the ratio of 93.5 to 100; and it is a better conductor, so that heat penetrates to a greater depth in the sea in the same space of time than it does in fresh water. The maximum density of sea water occurs at 4° F. below freezing, and its density increases regularly with falling temperature down to this point of congelation. It is different with fresh water, which actually expands as the temperature decreases from 39° to 32°, but contracts in volume with falling temperatures that are above 39° and below 32° F., if in form of ice.

CONVECTION IN WATER.—When only the upper surface of a body of water is heated it retains its position, because heat has expanded its volume and thereby reduced its specific gravity. It floats upon the colder and heavier water below much as a piece of wood would float, and stays there unless there be currents with vertical components of motion, or considerable agitation of the surface by winds. When the surface cools a contrary tendency exists; it contracts—except in the case of fresh water between 39° F. and 32° F. Contraction causes it to gain in density, and being heavier than the warmer water below, it sinks and water of less specific gravity comes up to take its place, which in turn parts with some of its heat to the colder air and descends. Thus, when the air is colder than the water, or when the surface layer cools by radiation at night, a circulation is established which continues in fresh water until every part of the body of water has fallen to 39° F., and in salt water to 28° F. At these temperatures the two waters reach their maximum density.

THE FREEZING OF FRESH AND OF SALT WATER.—With the further cooling of *salt* water below 28° F. particles of ice form; these expand in the process of freezing to a greater volume than was occupied by the water of which they are composed, and they therefore float upon the surface.

With the cooling of *fresh* water below 39° F. the law that holds good for all higher temperatures is reversed, and expansion of volume begins, which continues until a temperature of 32° is reached; therefore, cold fresh water of any temperature between 39° and 32° may float upon water that is considerably warmer. At 32° it has a less specific gravity than at 46°. At the temperature of 32° a change of state takes place, and that that was a liquid becomes a solid, and still further suddenly *expands its volume* in the process of change. The surface of a body of water does not freeze until every part of the body of the water that is subject to convectional circulation reaches the temperature of its maximum density, which, as previously stated, is 39° for fresh water and 28° for salt water.

The thermal conditions of rivers, lakes, and sea-lochs, or fjords, is well described and illustrated in Hugh Robert Mill's "Realm of Nature," pp. 164 to 172. Mill has shown that the lochs of Scotland, which are filled with sea water much freshened on the surface by numerous small mountain streams, cool on their surfaces as winter approaches, but, since the water is comparatively fresh, it continues to float on the warmer sea water below. The latter, because of its salinity, maintains a greater specific gravity than the chilled fresh water above. Convection does not operate freely, as it would if the lighter water were below. In many cases the water of these lochs is prevented from circulating with the cold water of the deep ocean by bars or sills which rise, at the entrance to the loch, nearly to the surface. In such cases the fresh water may freeze, while the salt water that is below the level of the bar retains a temperature of 45° or more.

The Temperature of the Great Oceans.—Because of the displacement of oceanic isothermals by ocean currents, it is impossible to name a definite temperature as prevailing over oceans at all places on a given parallel of latitude. But in a general way it may be stated that at the equator there is a surface temperature of 82° to 84° F., which changes less than a degree between day and night, and not over 5° between winter and summer; at a depth of 400 fathoms the temperature is 44° and unchangeable, and below 1,000 fathoms it is a little above the freezing point of fresh water—namely, 34° to 36°. In the middle latitudes the surface variation is from 50° in winter to 68° in summer. At latitude 70° N. the surface temperature has but a small diurnal variation, and a yearly range of from 35° for winter to 45° for summer; at a depth of 400 fathoms it remains steady at 32°. From this level there is a gradual decrease to a depth of 1,000 fathoms, where a constant temperature of about 28° exists, and below this to the bottom there is no change. One may get an idea of the enormous volume of cold water that lies upon the surface of the earth from the statement that about three fourths of the earth is covered with oceans, whose depths average about two miles, and in some places five miles, and whose temperatures below one mile are always close to the freezing point.

The temperature of inclosed seas is fairly well represented by the thermal conditions of the Red Sea, which extends in a nearly north and south direction, approximately one half of it lying in the tropics, being 1,450 miles long and about 180 miles wide. It receives heat from the hot radiating land that confines it to a long channel, which is narrow in comparison with other inland seas. Only the surface water of the Indian Ocean on the south is able to enter to take the place of the large amount that evaporates, for at its southern extremity a bar or sill, which extends from the bottom to within 200 fathoms of the surface, separates the deep water of the sea from that of the outside ocean. Its surface temperature varies from 85° in summer to 70° in winter, which is about the same as that of the Indian Ocean. Both bodies decrease in temperature at about the same rate down to the level of the sill, where the temperature remains constant at 70° the year through. Here their thermal similarity ceases, for the Red Sea, which has a depth of 1,200 fathoms, maintains a temperature of 70° from the top of the sill all the way down to the bottom, while the ocean continues to decrease in temperature down to a depth of at least 1,000 fathoms, where a temperature of 34° to 36° F. prevails without variation.

In a comparison between the Mediterranean and the basin of the Atlantic, a similar condition is found to exist. The sill at the entrance to the Mediterranean is 190 fathoms below the surface, at which level the temperature of both bodies is equal to 55° F. In the Mediterranean this temperature continues clear down to the bottom, while the temperature of the Atlantic at the same level as that of the bottom of the Mediterranean is only 35°.

In Lake Superior, which has an average depth of 900 feet, the temperature below the level of 240 feet remains unchanged throughout the year at 39°.

THE SHORE TEMPERATURE OF WATER is much affected by the direction of the wind. If the wind is onshore it skims off the warm water for a considerable distance out at sea and drives it shoreward, where it banks up, and, pressing downward, causes the colder water beneath to flow back seaward. Therefore, if the wind continues onshore for some hours, warm water finally displaces all of the cooler water lying near the shore line. In a like manner, offshore winds gradually blow off the top water near the shore and send it out to sea, and the colder water rises to take its place.

THE TEMPERATURES OF RIVERS closely follow those of the land over which they flow. They are, therefore, subject to considerable diurnal range, the amplitude of which depends on the depth of the stream, its width and its velocity, but is always less than that of the land.

The Temperatures of the Earth's Crust.—The earth's crust is a poor conductor and a poor radiator, and, since it differs from water in being impenetrable to solar radiation and when dry does not get the cooling effect of evaporation, its surface rises to a much higher temperature under the action of sunshine than does a water surface, or the adjacent air, or the stratum of soil immediately below the surface. The fact that soil differs from water in being an extremely poor reflector still further adds to the intensity of its surface heat. The heat that is conducted downward decreases in intensity, until it ceases to be apparent at a depth that is variable, but everywhere less than 50 feet, the exact distance depending on not only the amount of insolation at the surface but on the moisture content, conductivity, and specific heat of the strata of earth it passes through.

DEEP EARTH TEMPERATURES.—For some distance from the poles the earth is mostly covered with snow or ice during the entire year, and in the interior of Siberia frost prevails to very great depths, and only a thin surface thaws out under the summer heat.

Starting at the depth where the heat from the surface becomes inappreciable and proceeding downward, there is found an increase of temperature. In some places it has been found to be as much as a degree for each 40 feet, and in others as little as a degree for over 100 feet. The average is probably about 1° for each 60 feet. At this rate of increase water at normal pressure would boil at a depth of 9,500 feet; and all rock would be melted at a depth of 30 miles, unless, as is more than likely the case, the pressure of the earth above holds it in the solid form. Near Berlin the temperature at the depth of 3,490 feet was found to be 116°; while at about the same depth in a boring at Wheeling, W. Va., the temperature was 108°. In neither place is there a daily or annual variation.

HEATING OF THE SOIL BY DECOMPOSITION OF ORGANIC MATTER.—The surface temperatures of the soil may be affected by the heat given out by decaying manure or vegetation, as shown by Mr. C. C. Georgeson in a description of some experiments made at Tokyo, Japan, where an acre of ground covered with 80 tons of manure was soon observed to have a temperature 5° F. higher than that of adjacent unmanured ground, the difference steadily growing less but being appreciable at the end of two months.

COMPARISON OF TEMPERATURES OF SOIL AND AIR.—The following figures give the hourly mean temperatures of the soil and of the air about 10 feet above it, which were observed at Tiflis (lat. 41° 43′ N., elevation 410 m.):

TABLE XI.

TIME.	WINTER. (December to February.)			SUMMER. (June to August.)		
	Soil.	Air.	Soil Warmer or Colder than Air.	Soil.	Air.	Soil Warmer or Colder than Air.
1	32.4	34.7	−2.3	66.6	66.0	+0.6
3	31.6	34.0	−2.4	64.6	64.4	+0.2
5	31.1	33.4	−2.3	63.7	63.5	+0.2
7	30.6	32.9	−2.3	73.6	66.9	+6.7
9	37.4	35.6	+1.8	94.5	72.3	+22.2
11	50.5	40.3	+10.2	113.2	76.6	+36.6
1	55.8	43.9	+11.9	120.2	79.3	+40.9
3	51.6	45.1	+6.5	113.7	80.4	+33.3
5	39.7	42.1	−2.4	96.4	79.3	+17.1
7	35.4	38.8	−3.4	79.0	74.8	+4.2
9	34.2	36.9	−2.7	72.1	70.7	+1.4
11	33.1	35.8	−2.7	68.9	68.2	+0.7
Mean	38.7	37.8	+0.9	85.5	71.8	+13.7

TEMPERATURE OF THE SOIL AFFECTED BY PRECIPITATION.—The change in the temperature of the soil may be considerable when precipitation, in the form of either rain or snow, carries much of the heat liberated by condensation down to the earth. Even then the warming or the cooling of the ground depends on whether or not the ground is cooler or warmer than the rain or the snow. In general the ground will be warmer even in winter than that which is precipitated upon it.

COOLING OF THE SOIL BY EVAPORATION AND MELTING.—Evaporation from a moist soil and the melting of snow produce a pronounced cooling effect because of the quantity of heat employed and thereby rendered latent.

DIURNAL VARIATIONS OF EARTH TEMPERATURES.—There are seasonal temperature oscillations in the thin top crust of the earth due to heating during summer and cooling during winter, and there are also irregular oscillations due to protracted cloudiness, abundant rainfall, and snow covering.

By day the surface of the earth is heated and at night it is cooled; there is, therefore, a diurnal wave of temperature which is propagated toward the interior. Since the surface temperature is a periodic function of the time, the temperature at any depth will vary in a corresponding periodic manner, the *amplitude of the wave*[1] decreasing as it progresses downward.

At latitude 45° the diurnal changes are not felt below a depth of 3 feet.

The following laws are in close accord with observed facts:

First Law: The diurnal amplitude of oscillation of temperature decreases in geometric progression as the depth increases in arithmetic progression.

Example

Suppose daily amplitude at the surface to be 28° F.

And at a depth of $\frac{1}{3}$ foot, 14° F., or $\frac{1}{2}$ of 28° F.

At a depth two times the above, or $\frac{2}{3}$ foot, the amplitude will be reduced to $\frac{1}{4} \times 28 = 7°$; at three times, or 1 foot, to $\frac{1}{8} \times 28 = 3.5°$. At this rate diurnal variation will be inappreciable at 3 feet.

Second Law: The lag of the maximum and minimum epochs is proportional to the depth.

Example

Usually the maximum surface temperature will occur at 1 P.M. Assume that at a depth of $\frac{1}{3}$ foot it occurs at 3 hr. 40 min. P.M.

At $\frac{2}{3}$ foot the lag is double, making the time 6:20, or 6 hr. 20 min. P.M.

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[1] Difference between the highest and the lowest temperatures.

At the same rate of retardation the maximum at a depth of 1⅔ feet will occur 13 hr. 20 min. late—viz., 2 hr. 20 min. A.M.

ANNUAL VARIATION OF EARTH TEMPERATURES.—At the depth of 30 or 40 feet the temperature everywhere and at all times is about the same as the mean annual air temperature. Deep-flowing springs also have about this same temperature. Springs supplied with water from moderate depths may also be not far from the normal air temperature, except where the surface of the ground is blanketed with snow for a considerable period during the time when the air temperature is much below freezing; then their flow has a temperature above the normal air temperature. In the middle and in the higher latitudes the monthly means of surface temperatures of the ground are higher than are those of the air, the greatest difference being in August and the least in January. At a depth of 3 feet the means are about 2° F. higher than are those of the air near the surface. The temperature shows no change from day to day and year to year in the Mammoth Cave, Kentucky, where it is 54° F. For a long period of time it has not varied from 53.3° at a depth of 90.6 feet in the cellar of the Paris observatory. Fig. 21 shows the mean monthly gradients of earth temperatures to a depth of 10 feet at Oxford, England.

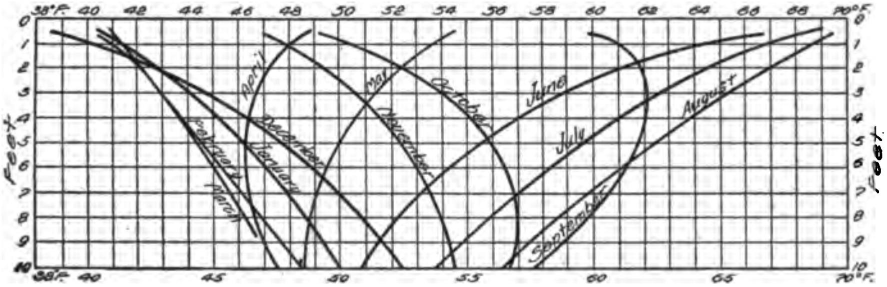

FIG. 21.—MEAN MONTHLY GRADIENTS OF EARTH TEMPERATURES (Radcliffe Observatory, England, 1892–1899).

Third Law: If we consider oscillations having different periods—(*a*) *Their amplitudes are reduced in the same proportion at depths proportional to the square roots of the respective oscillation periods.* (*b*) *The lag of the maximum or minimum is equal to the same fraction of the oscillation period, if in each case we observe at depths proportional to the square roots of the oscillation periods.*

Example

(*a*) Take the diurnal and annual oscillations at different depths. The year contains 365.25 days, and the square root is 19.1. The diurnal amplitude being reduced to ½ at a depth of ⅓ foot, the annual amplitude (according to the third law) is reduced to ½ at $\frac{1}{3} \times 19.1 = 6.34$ feet; it will be reduced to ¼ at a double depth, or 12.68, and so on. (*b*) The lag of the diurnal period is shown to be two hours and forty minutes at a depth of ⅓ foot; this is ⅑ of the diurnal period for twenty-four hours. It will be, then, for the annual oscillation ⅑ of the period, or $\frac{365.25}{9} = 40.6$ days at the depth of 6.34 feet; and it will be six months at a depth of $1\frac{1}{2} \times 19.1 = 28.65$ feet. Hence, at 28.65 feet the maximum will occur at the time of minimum at the surface.

In applying these three laws relative to the movement of thermal waves in the earth it should be remembered that the rate of propagation and the amplitude depend in considerable measure on the composition of the soil and the rock and on the moisture content. Snow is a bad conductor and prevents the escape of heat; this explains why frost descends deeper when the soil is exposed than when it is covered with snow.

The lag of temperature in the stratum that is subject to an annual variation is shown for the region about Munich, Bavaria, in the work of Karl Singer. The results were deduced from observations that extended through a period of thirty years, at the observatory of Bogenhausen. At a depth of 4.2 Bavarian (4.0 English) feet the minimum annual temperature occurs on the 2d of March; the maximum on the 24th of August. For each step downward of 4 feet, the occurrence of the epoch of extreme temperature is retarded on an average of twenty-one days, the minimum at a depth of 20.2 feet occurring on the 23d of May, and the maximum on the 17th of November. At the 4.2-foot level the lowest temperature recorded was 36° F. and the highest 63°; while at the lowest level (20.2 feet) the absolute range was much less, the extremes being 45° and 52°.

Dr. W. Oishi,[1] Meteorologist of the Central Meteorological Observatory of Japan, has studied a series of systematic observations of earth temperatures, made at Tokyo, that cover a period of more than fifteen years (1886–1902).

As in the case of daily temperature range, so also the annual range decreases rapidly under the ground, and the times of occurrence of maximum and minimum temperatures are retarded gradually.

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[1] In the *Monthly Weather Review*, July, 1905, Dr. S. Tetsu Tamura gives an excellent review of memoirs on the earth temperature observations by his compatriots, from which the information relative to these observations in Japan is gleaned.

TABLE XII.

Annual Range and Lag of Earth Temperatures at Tokyo, Japan.

DEPTH IN FEET.	Annual Range. °F.	TIME OF OCCURRENCE.	
		Maximum.	Minimum.
0.0	50.8	Aug. 11	Jan. 23
1.0	40.9	Aug. 16	Jan. 23
2.0	33.7	Aug. 21	Jan. 31
3.9	25.2	Sept. 15	Feb. 27
9.8	9.4	Nov. 6	May 3
16.4	2.3	Feb. 2	July 30
23.0	0.7	April 30	Oct. 30

Fig. 22 illustrates the variations in the temperature of the air, of the surface water of the River Elbe, and of the earth, at Hamburg, down to 16.4 feet.

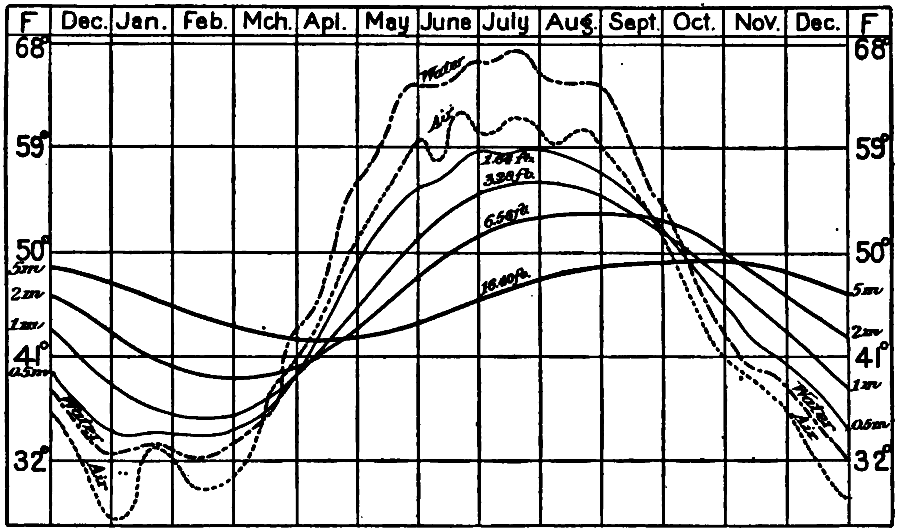

FIG. 22.—TEMPERATURE OF THE AIR, OF THE SURFACE WATER OF THE RIVER ELBE, AND OF THE EARTH AT DIFFERENT DEPTHS, AT HAMBURG. (Van Bebber.)

Variations in Minimum Air Temperatures Over Snow.—Snow being an excellent nonconductor of heat, one might expect to find a fairly homogeneous distribution of temperature throughout the stratum of air 5½ feet above snow and covering the area of a single village; and such is the case whenever there is a sufficient movement of wind to thoroughly mix the air. But on clear nights, with but little wind, remarkable differences of temperature may be found by comparing thermometers exposed in close relation the one to the other. These differences cannot be better illustrated than by referring to an investigation that was made by Prof. Willis I. Milham, Ph.D., in charge of the coöperative station of the U. S. Weather Bureau at Williams College, Mass., in the winter of 1904–05.[1]

The observations were taken on thirty-six nights when the temperature fell to near zero.

The greatest estimated wind velocity, 12 miles per hour, occurred on January 26th, and the least variation in the observed temperatures—namely, 1° F.—was also observed on that date. The three next greatest estimated wind velocities, 10 miles on January 4th, 6 miles on February 3d, and 4 miles on February 19th, had corresponding variations of 2.2°, 2°, and 2.2°, respectively. These variations are much less than the average variation—namely, 5.1°. The expectation that wind would thoroughly mix the lower layers of the atmosphere and render the temperatures for different elevations at different localities fairly uniform, is thus verified by the observations.

The greatest difference between the several thermometers—namely, 10° F.—occurred on January 23d. There were 6 inches of snow on the ground. The wind was blowing gently from the northwest and the sky was cloudless. The next five largest differences were, namely, 9° on December 15th, 8° on December 19th, 9° on December 22d, 7.5° on February 12th, and 8° on February 15th. In these cases the wind changed to brisk east or southeast during the night and the sky became overcast, and some instruments showed a rise of 20° in temperature. It would seem that the east wind displaced the cool air of the more elevated stations with warmer air, while the cold air in the depressions remained.

Professor Milham concludes, as one might expect, that while elevation is the most important factor, the openness of the valley, and its direction with relation to the course of the wind, played a part in determining these minimum temperatures. The highest station was not the warmest and the lowest station was not the coldest. Hence the stations could not be arranged in the order of coldness depending upon their elevation alone. Furthermore, he found that during the still, clear nights of winter a registering minimum thermometer exposed in the standard thermometer shelter read on the average between 3° and 4° higher than the same instrument exposed in the open.

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[1] Published in the *Monthly Weather Review*, July, 1905.

Adiabatic Heating and Cooling of the Air.—When the pressure upon a mass of air is decreased the air expands; to effect this expansion, which involves the performance of work, a part of the heat energy of the air is utilized and becomes insensible as heat; hence the air becomes cooler or its temperature falls as a result of the expansion. If we imagine a definite quantity of the atmosphere elevated above the surface of the earth, it will come under a diminished pressure (having less air above it), and will consequently expand and cool. Now it is found that dry air will cool about 1° F. by a diminution of pressure equal to that involved in a change of altitude of 183 feet. On the other hand, if a mass of air is carried downward 183 feet, it will be compressed into less space by the superincumbent air, and the heat energy that was employed in expanding to its former larger volume will be restored to its original duty and appear as sensible heat; wherefore air becomes warmer or its temperature rises under compression.

This process, which involves no addition from, or loss to, outside space is called *adiabatic heating or cooling*. The normal rate is, then, 1° F. for an ascent of 183 feet. When the air contains moisture, however, the rate is changed by the latent heat rendered sensible when a portion of the contained vapor is condensed. Hence, in free air, the change usually is less than for dry air.

The Average Seasonal Altitude of the Frost Level in the Free Air.—The altitude of the frost level, or the stratum of freezing temperature, in the free air, over the equator, for January, is shown by Fig. 23, as is the sloping away of this level to the northward and to the southward, and the latitude where it touches the earth along the meridian of Greenwich. The same conditions are shown for July by Fig. 24. Of course the parts of the figures that show these altitudes are much exaggerated. It will be observed that the frost level remains unchanged over the equator at 18,000 feet, during winter and summer, but that it rises and falls with the seasons north and south of the equator, the amplitude of the movement increasing with latitude and being greater along meridians that pass over continents than along those that pass over oceans. The dotted line on Fig. 23 represents the conditions as they exist along a part of the 90th meridian, which passes through the interior of North America. In the southern hemisphere both the 90th and the Greenwich meridians pass mainly over water, and therefore the vertical distribution of temperature along them is the same; but in the northern hemisphere the Greenwich meridian passes almost entirely over water and the 90th meridian mostly over land,

and consequently a considerable difference exists in the temperature of the air over them. This is shown by comparing the dotted line on Fig. 23 with the full line above it, which latter line represents the elevation of

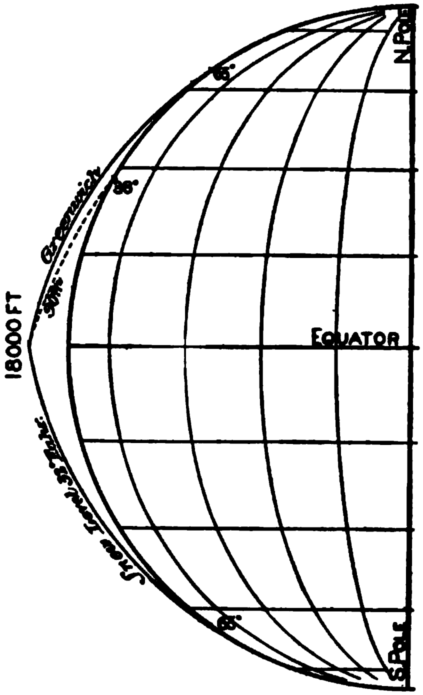

FIG. 23.—MEAN JANUARY HEIGHT OF FROST OR SNOW LEVEL ALONG GREENWICH AND 90TH MERIDIANS.

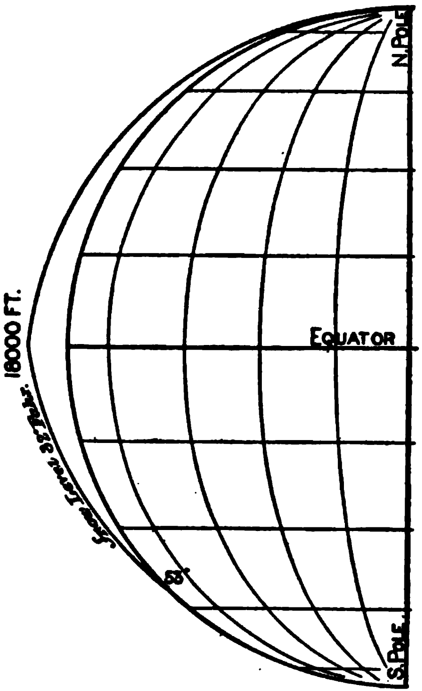

FIG. 24.—MEAN JULY HEIGHT OF FROST OR SNOW LEVEL ALONG GREENWICH MERIDIAN.

the stratum of freezing temperature from the equator northward along the Greenwich meridian.

The land losing heat by radiation so much faster than the water, and the thermal conditions of the air to the height of several thousand feet following in considerable measure those of the earth beneath, the average temperature for January brings the frost level down to the surface of the land at 38° latitude, while this level does not touch the ocean on the Greenwich meridian below 65°. However, it would not reach so far north were it not for the influence of the circulation of the Atlantic Ocean, which carries large quantities of heat northward from warm latitudes and then parts with it to the air. The poleward current that passes between the British Islands and Greenland pushes northward the point where the frost level touches the surface in the region of the Greenwich meridian about

12° of latitude. This fact is made apparent by noting that this level comes to the earth at latitude 53° in the southern hemisphere during winter (Fig. 24). The frost level reaches the surface at latitude 65° in the southern hemisphere (Fig. 23) during January, but touches the pole in the northern hemisphere (Fig. 24) during the like season (July). It is apparent that the winters of the northern hemisphere are cooler than those of the southern hemisphere, and that the summers are warmer than are the same seasons in the south half of the globe. This is due to the much greater area of land surface in the northern hemisphere.

Vertical Decrease of Temperature as Determined by Balloons and Kites.—From the temperature records obtained during 722 balloon ascensions near Paris, France, the temperatures at various heights were determined as follows:

TABLE XIII.

Vertical Decrease of Temperature Near Paris.

HEIGHT.		TEMPERATURE.					FEET PER 1° F.	
Meters.	Feet.	Winter.	Spring.	Summer.	Autumn.	Year.	Between Levels.	From Surface.
Surface		35.2° F.	41.2° F.	55.8° F.	46.0° F.	44.5° F.		
3,000	9,842	19.2° F.	19.6° F.	35.4° F.	28.4° F.	25.6° F.	521	521
4,000	13,123	10.0° F.	9.3° F.	26.6° F.	19.4° F.	16.3° F.	353	465
5,000	16,404	−1.1° F.	−2.0° F.	16.2° F.	8.8° F.	5.5° F.	304	421
6,000	19,685	−13.0° F.	−14.1° F.	5.0° F.	−2.6° F.	−6.2° F.	280	388
7,000	22,966	−26.7° F.	−26.7° F.	−7.6° F.	−15.2° F.	−19.0° F.	256	363
8,000	26,247	−39.8° F.	−39.3° F.	−21.3° F.	−28.8° F.	−32.3° F.	246	342
9,000	29,527	−53.0° F.	−52.4° F.	−36.4° F.	−42.9° F.	−46.2° F.	236	325
10,000	32,808	−64.3° F.	−61.2° F.	−49.4° F.	−54.9° F.	−57.4° F.	293	322

From 75 balloon ascensions near Berlin the following temperatures were obtained:

TABLE XIV.

Vertical Decrease of Temperature near Berlin.

HEIGHT.		TEMPERATURE.			FEET PER 1° F.	
Meters.	Feet.	Winter and Spring.	Summer and Autumn.	Year.	Between Levels.	From Surface.
Surface		40.1° F.	56.8° F.	50.2° F.		
3,000	9,842	14.5° F.	30.6° F.	23.0° F.	362	362
4,000	13,123	5.9° F.	20.5° F.	13.5° F.	345	349
5,000	16,404	−4.0° F.	8.2° F.	2.1° F.	288	341
6,000	19,685	−21.6° F.	−3.1° F.	−11.6° F.	239	319
7,000	22,966			−20.9° F.	353	323
8,000	26,247			−36.9° F.	205	301
9,000	29,527			−51.5° F.	225	292

The mean fall in temperature per 1,000 feet up to a height of 20,000 feet is, from the Paris records, 2.4° in winter, 2.8° in spring, 2.6° in summer, 2.5° in autumn, and 2.6° for the year. From the Berlin records it is 3.1° winter and spring, 3° in summer and autumn, and 3.1° for the year.

According to the results of a detailed study by Humphreys of sounding balloon records, seasonal effects on the distribution of temperature in the atmosphere extend from the surface of the earth, where they are most pronounced, to unknown heights—possibly to the limit of the atmosphere, since after the isothermal region is reached, where they are still about half

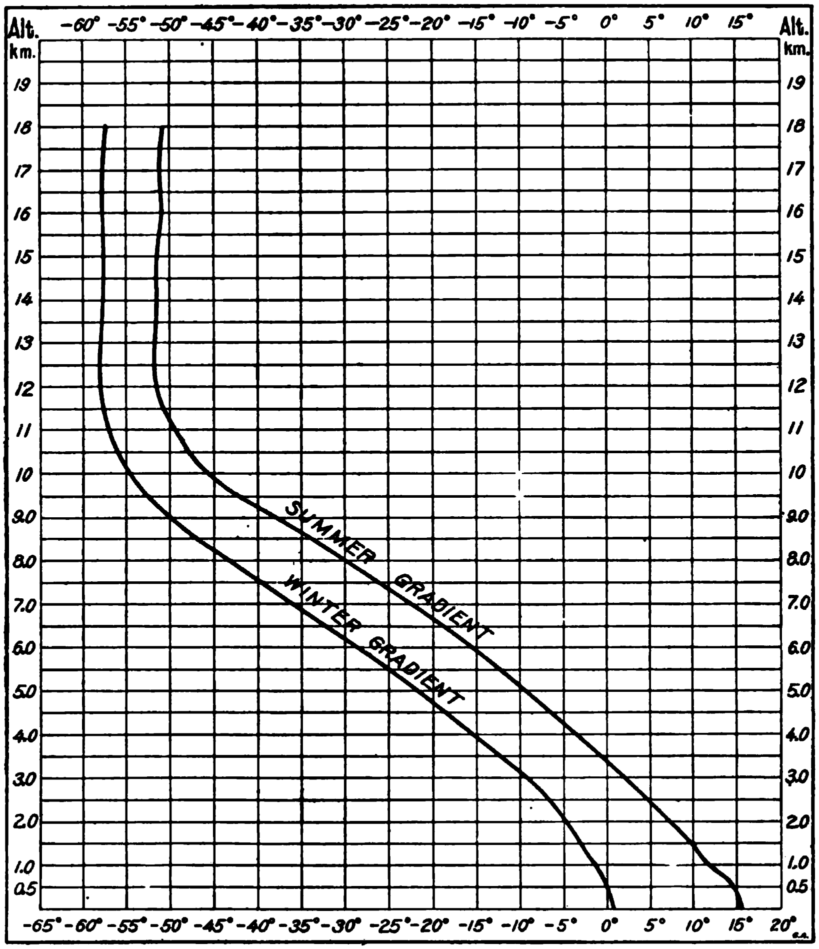

FIG. 25.—SUMMER AND WINTER VERTICAL GRADIENTS OF TEMPERATURE.

as great as at the surface, they remain essentially constant at all elevations so far attained by sounding balloons.

Fig. 25 gives the average of 52 winter (December, January, February, and March) and of 65 summer (June, July, August, and September) temperature gradients, obtained by sounding balloons sent up at about the same time of day, 8 o'clock A.M., from Munich, Strassburg, Trappes, and Uccle—places of approximately the same latitude. These include all the summer and winter flights that up to the present (August, 1909) have been published in detail from the above stations, and are sufficient in num-

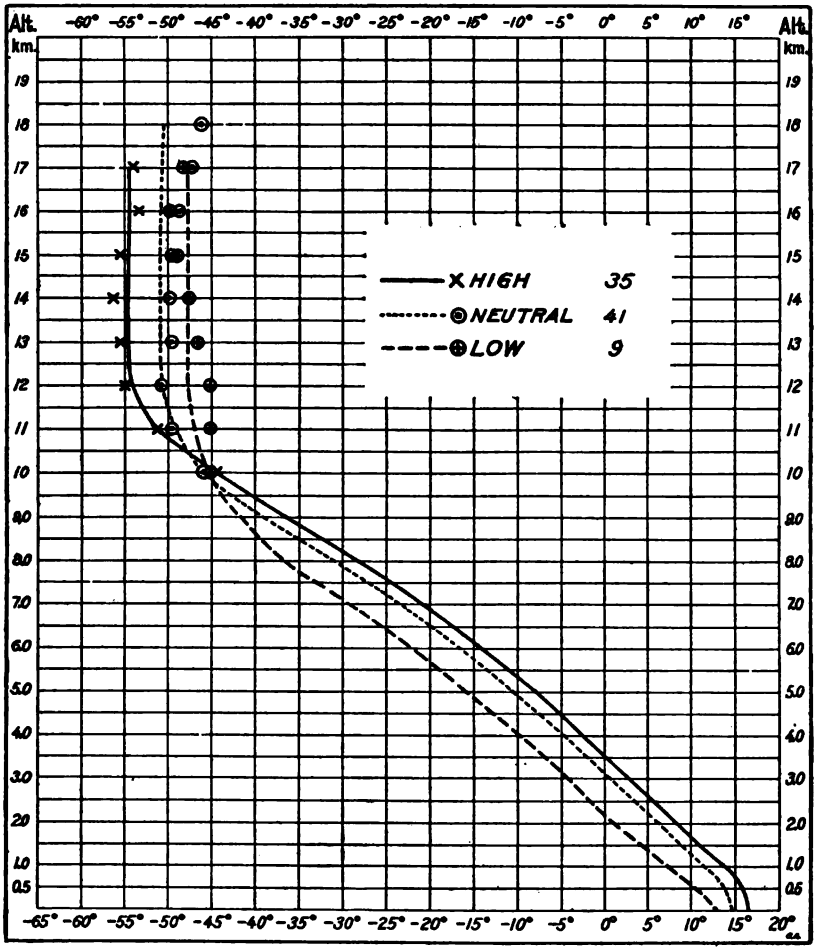

FIG. 26.—TYPES OF SUMMER VERTICAL GRADIENTS OF TEMPERATURE.

ber, presumably, to give entirely trustworthy averages. It will be seen from the figure that the temperature decreases with elevation less rapidly near the surface of the earth, and more rapidly between 4 and 8 kilometers elevation during the winter than during the summer; that the isothermal region is at lower levels during the winter, and that it is then decidedly colder.

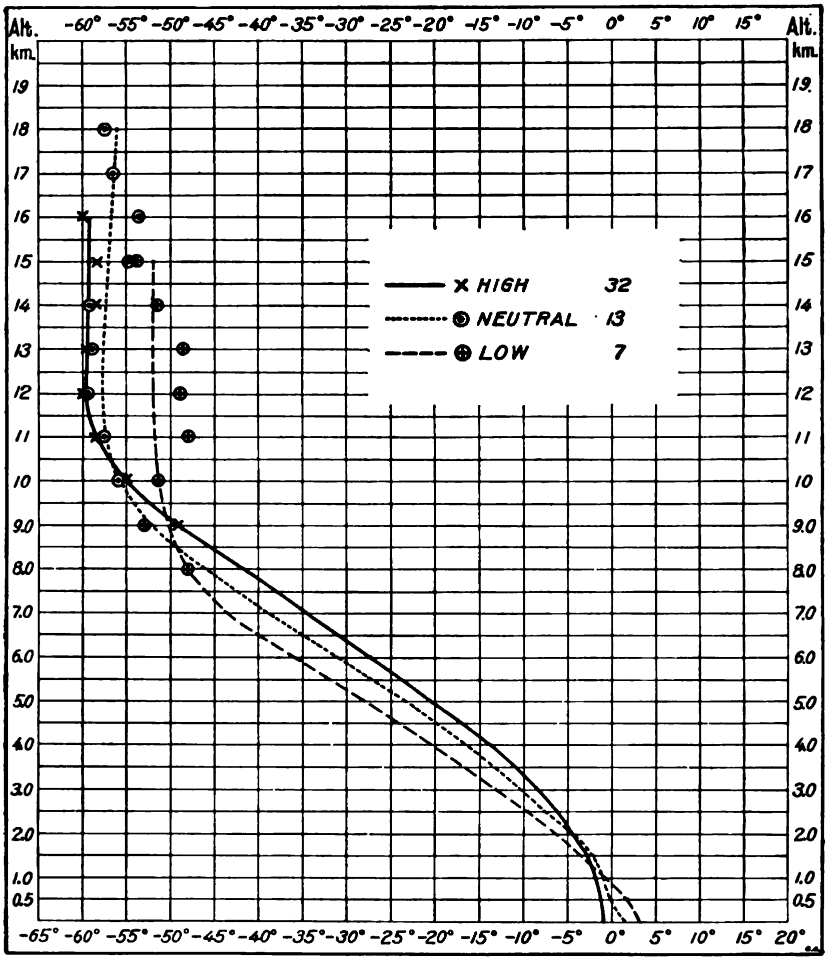

FIG. 27.—TYPES OF WINTER VERTICAL GRADIENTS OF TEMPERATURE.

EFFECT OF STORMS ON VERTICAL DISTRIBUTION OF TEMPERATURE.—That the distribution of temperature in the atmosphere is also dependent upon storm conditions is shown by Figs. 26 and 27. In each of these the continuous line gives the typical vertical temperature gradient in the region of high pressure or during fair weather; the broken line the gradient in the region of low pressure or during foul weather; while the dotted curve applies to neutral conditions.

It will be noticed that a high barometer (clear weather) always leads to a greater elevation and lower temperature for the isothermal region than does a low barometer; that at middle elevations it gives higher temperatures at all times; and that at and near the surface it causes higher temperatures in the summer and lower temperatures in the winter.

All these effects can be accounted for through convection, condensation, and radiation, but as an adequate discussion of the physical processes involved lies outside the province of descriptive meteorology, the interested reader must therefore consult the original journal articles that discuss this subject.

Valuable results have been secured by Mr. A. Lawrence Rotch, with kites, at Blue Hill, near Boston. In 1898 the U. S. Weather Bureau secured records from over 1,200 flights with kites during the six warm months from May to October. Seventeen stations, scattered through a broad expanse of territory, were in continuous operation. These observations were discussed by Prof. H. C. Frankenfield, and the results published in Bulletin F, 1899. Some of the results, showing the temperature gradient up to a height of 5,280 feet, are given in Table XV, which follows:

TABLE XV.

Vertical Temperature Gradient for Warm Months in the United States.

STATIONS	Altitude of Station Above Sea Level. Feet.	TEMPERATURE.	
		Gradient per 1,000 Feet.	Reduction for 1 Mile.
Washington	210	−3.00° F.	−15.2° F.
Cairo	315	−4.30° F.	−25.6° F.
Cincinnati	940	−5.15° F.	−27.5° F.
Knoxville	990	−5.00° F.	−21.5° F.
Memphis	319	−3.50° F.	−17.3° F.
Springfield	684	−3.85° F.	−17.7° F.
Cleveland	705	−4.10° F.	−18.8° F.
Duluth	1,197	−4.30° F.	−17.6° F.
Lansing	869	−3.85° F.	−17.0° F.
Sault Ste. Marie	722	−3.45° F.	−15.7° F.
Dodge	2,473	−4.10° F.	−11.6° F.
Dubuque	894	−3.30° F.	−14.5° F.
North Platte	2,811	−5.40° F.	−13.3° F.
Omaha	1,241	−3.20° F.	−12.9° F.
Pierre	1,595	−3.90° F.	−14.4° F.
Topeka	972	−3.83° F.	−16.5° F.

In this table the second column gives the altitude of the ground at the reel on which the kite wire was wound. The third column shows the average gradient in degrees Fahrenheit per 1,000 feet above the reel at the respective stations, up to a uniform surface 5,280 feet above sea level. The fourth column shows the total reduction to be applied to the temperature at the reel in order to obtain the temperature at the one-mile level above sea. At the observatory at Trappes free balloons and kites were used by L. Teisserenc de Bort during eighteen months, in 1898 and 1899, with sufficient frequency to give us some knowledge of the monthly gradients of temperature in a vertical direction and the average gradient for the year. The following results (Tables XVI, XVII, and XVIII) are taken from the *U. S. Monthly Weather Review,* September, 1899:

Table XVI.

Vertical Decrease of Temperature at Trappes, France.

Altitude Above Ground.		Annual.	May–October.	November–April.
Kilometers.	Miles.			
10	6.2	108.2° F.	114.7° F.	101.7° F.
9	5.6	92.5° F.	98.1° F.	86.9° F.
8	5.0	80.5° F.	85.0° F.	76.0° F.
7	4.3	76.9° F.	71.1° F.	64.4° F.
6	3.7	54.4° F.	56.0° F.	52.6° F.
5	3.1	43.6° F.	45.5° F.	41.8° F.
4	2.5	32.9° F.	35.8° F.	30.1° F.
3	1.9	23.8° F.	27.5° F.	19.8° F.
2	1.2	15.5° F.	18.5° F.	12.2° F.
1	0.6	7.2° F.	10.3° F.	4.1° F.
0	0.0	0.0° F.	0.0° F.	0.0° F.

Mountain Tops Cooler than Free Air of Same Level.—Wherever observations have been made they have shown that the temperature of the air on high mountain peaks and crests and for a distance of 100 to 300 feet above them is appreciably cooler than adjacent free air of the same height, due to deflection of the winds and radiation of the peaks. It is, therefore, probable that the same conditions of coldness prevail over all mountains. Clayton, in an excellent series of observations at Blue Hill,[1] Mass., has shown that even at this station, which is only a little over 600 feet above sea level and 480 feet above the level of the valley, the temperature at night is lower than that of the free air at the same elevation over the valley, the difference often being as much as 2°, 5°, or 7° F.; and when the decrease of temperature with elevation in the free air was less

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[1] *Annals of the Astronomical Observatory of Harvard College,* vol. lviii, Part I.

Table XVII.

Mean Minimum and Mean Maximum Temperatures (1890–1894) *at the Parc St. Maur, Paris, and on the Eiffel Tower.*[1]

	Park St. Maur. (Altitude Above Ground, 6 feet; Sea, 167 feet.)		Eiffel Tower.					
			First Platform. (Altitude Above Ground, 404 feet; Sea, 514 feet.)		Second Platform. (Altitude Above Ground, 645 feet; Sea, 755 feet.)		Summit. (Altitude Above Ground, 991 feet· Sea, 1,100 feet.)	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
January	32.5	38.9	33.3	37.7	33.3	36.8	33.1	35.5
February	35.0	45.0	35.9	42.9	36.1	41.9	35.8	39.9
March	37.0	51.3	38.5	48.7	38.7	47.5	38.6	45.6
April	42.0	60.2	41.1	56.9	44.2	53.8	44.7	53.9
May	47.5	64.1	49.4	60.9	49.2	59.4	49.3	58.0
June	52.9	69.9	55.1	66.7	54.9	65.4	54.4	63.8
July	55.5	71.3	57.2	68.4	56.8	66.9	56.6	65.5
August	55.2	72.2	57.3	69.8	57.7	68.4	57.6	66.9
September	50.8	67.3	53.5	65.1	54.1	64.0	54.4	62.2
October	45.3	56.6	46.8	55.0	47.3	53.9	47.1	52.1
November	40.2	47.5	40.8	45.8	40.6	44.8	40.3	43.0
December	32.7	39.0	33.6	37.8	33.4	37.1	33.4	35.9

Table XVIII.

Absolute Maximum Temperatures on Eiffel Tower and in Parc St. Maur.[2]

Year.	Station.	June.	Absolute Max. Temp.	Fahr. Temp. at 3 P.M.	July.	Absolute Max. Temp.	Fahr. Temp. at 3 P.M.	Aug.	Absolute Max. Temp.	Fahr. Temp. at 3 P.M.
1890	Parc St. Maur	26	87.8	83.8	15	87.1	83.7	1	90.7	89.4
	Tour Eiffel	26	78.8	79.9	15	79.4	75.2	1	85.8	84.7
1891	Parc St. Maur	1	80.4	75.0	18	84.4	81.1	27	85.1	80.6
	Tour Eiffel	1	72.5	71.8	18	76.5	75.9	27	78.4	76.3
1892	Parc St. Maur	28	89.1	88.5	3	87.1	73.0	18	95.4	94.8
	Tour Eiffel	28	86.4	83.5	3	80.8	73.4	18	91.0	90.7
1893	Parc St. Maur	19	91.0	87.8	4	92.3	89.2	18	96.3	95.0
	Tour Eiffel	19	85.6	83.1	4	86.0	86.0	18	91.4	91.0
1894	Parc St. Maur	30	86.4	84.4	6	90.3	88.9	6	88.7	85.6
	Tour Eiffel	30	79.2	77.4	6	85.3	83.8	6	82.6	80.8

than the adiabatic rate, as it usually is, the cooling appeared above the top of Blue Hill in the daytime. When the kites were pulled in at night the kite-meteorograph generally showed a uniform rise of temperature with descent until it was within less than 150 feet of the top of the hill, when a sudden fall of temperature occurred. The mean temperature of the air above every peak that has been compared with the temperature of the free air of the same level has been found cooler than the free air, and it is probable that all mountains, by forcing the air to rise over them and to cool by expansion as it ascends—which cooling usually is at a greater rate than the vertical decrease of temperature of the free air—produce a cooling effect that more than compensates for the heat given to the air by conduction and radiation from the mountain. This effect must be greater when the direction of the wind forms a considerable angle with the direction in which the mountain trends, and be greatest when the incident winds encounter mountains at right angles to their direction of movement. On clear nights mountains are abnormally cooled by radiation.

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[1] (Fahr.). From *Annales du Bureau Central Météorologique de France,* 1894.

[2] *Annales du Bureau Central Météorologique de France.*

Diurnal Range of Temperature in the Free Air.—The average difference between the temperatures of day and those of night diminishes with ascent in the free air until at only a few thousand feet from the surface of the earth (3,000 to 5,000) there is no difference between the heat of midday and that of midnight. On the summit of the Eiffel Tower, which is 991 feet above the ground, the mean amplitude of the diurnal temperature is but 2.3° F. in January and 9° F. in July; while the amplitude for the same period in Parc St. Maur, near Paris, at an elevation of 6.7 feet above the ground, is 6.5° F. for January and 15.8° F. for July. Not only is the diurnal variation reduced at the top of the tower, but the hours of the maximum and minimum, especially the maximum, are considerably retarded as compared with those observed in the air near the surface of the earth. These conditions are due to the fact that the earth both absorbs and radiates heat more rapidly than does the atmosphere above it.

Diurnal Range of Temperature at the Bottom of the Atmosphere.—The diurnal range of temperature is greatest at the equator and decreases irregularly with latitude, being greater over land than over water on the same parallel. Neither does it regularly decrease with the elevation of the station; in fact, the lower air immediately over a high plateau may have a much greater range than that at the sea level. Over the plateaus the smaller amount of water vapor and of cloud offers less obstruction to the passage of insolation to the earth than the more humid conditions lower down, and the land is heated to a comparatively high degree of temperature during the daytime; and the conditions that permit the free ingress of heat under sunshine facilitate its escape during the night. Hence the wider diurnal range of temperature over plateaus than at sea level. The diurnal range on plateaus is greater that it is at the same level on sharp mountain peaks or in the free air at the same elevation as the peaks.

Valleys may show a greater range than hilltops, especially where the valleys are narrow and the sides precipitous, and when the sky is clear. Radiation from the mountain sides during the day may heat the interior to an ovenlike temperature, and at night the air, chilled by coming in contact with the cool vegetation or other surface higher up, contracts in volume, and, gaining in specific gravity, flows downward and collects in the valleys.

There may be a marked difference in the diurnal range of the two sides of a mountain. If one side receives winds that have first passed over a considerable body of water or moist earth, and become humid, clouds and other forms of precipitation may materially reduce the diurnal oscillation, while on the other side of the mountain, where the air arrives after having been considerably freed of its moisture, the diurnal range will be greater.

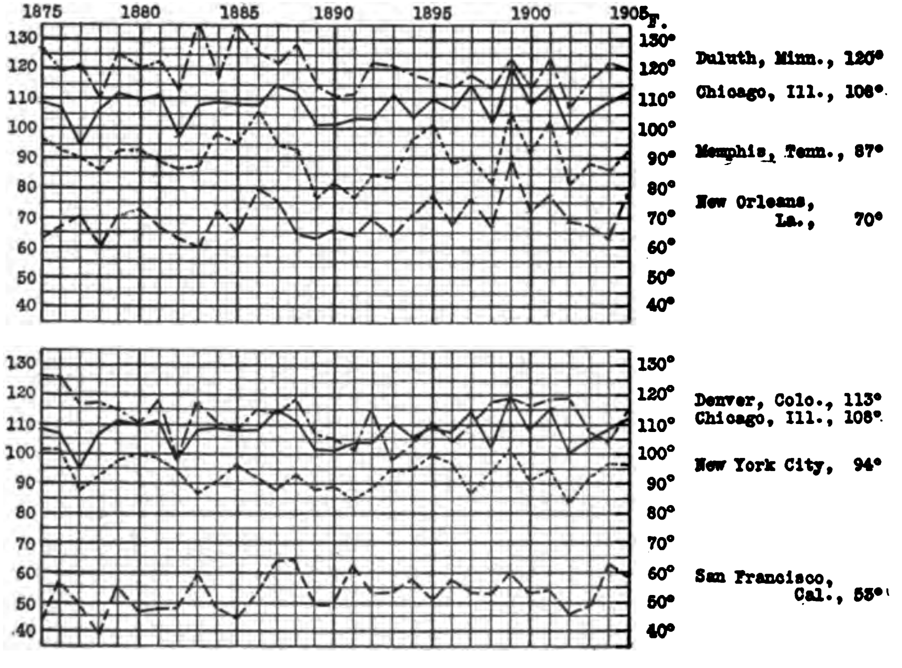

FIG. 28.—ANNUAL RANGE IN TEMPERATURE.

Annual Range in Temperature.—This is illustrated by Fig. 28, which shows the annual range in temperature at four selected stations in the United States in different latitudes, from Duluth on the north to New

Orleans on the south. The range in temperature steadily diminishes from north to south during each year of the entire period from 1875 to 1905, inclusive. The range in temperature is greatest in the northern sections, because of the extreme cold of the continental winter, there not being nearly as much difference between the summer temperatures in different latitudes in the United States as between winter temperatures. In fact, the maximum summer temperatures in the central part of the continent often exceed those observed farther south, where the inflow of aqueous vapor from the Gulf and the adjacent Atlantic Ocean tends to depress the summer temperatures, while in the winter there is, almost without exception, a well-marked and steady increase in temperature from north to south. That the humid air from the water, which modifies the summer heat, does not flow as far inland in winter as in summer is due to the fact that the preponderance of pressure is on the land during winter and on the gulf and ocean during summer.

The greatest extreme annual range of temperature occurs over Siberia. Wild shows that the absolute range[1] for Yakutsk is from —80° in January to + 102° in July, or a total of 182°, as compared with 222° (from —94° to + 128°) for the whole globe. Dawson, Canada, has a record of —68° in January, 1901, and of + 95° in July, 1899, giving an absolute range of 163°. Havre, Montana, has an equal absolute range, the minimum being —55° and the maximum + 108°.

At Jacobadad, India, the absolute range is 97°; at York, West Australia, it is from a maximum of 116° to a minimum of 27°, or 89°; at Cordoba, Argentina, from a maximum of 111° to a minimum of 16°, or 95°; while in Algeria, Africa, it varies from a maximum of 121° and a minimum of 23° near sea level, to a maximum of 113° and a minimum of 8° on the high plateau in the interior.

ANNUAL RANGE IN TEMPERATURE LESS UNDER MARINE INFLUENCE.—In contrast with these excessive ranges in the temperature over land areas the absolute range at Thorshaven, Faroe Islands, is from a maximum of 70° to a minimum of 11°, or 59°; at Apia, Samoa, from a maximum of 92° to a minimum of 62°, or 30°; while at some of the islands under the equator the absolute range is only 16°.

In the lower graph of Fig. 28 are lines showing the annual range in temperature during the period from 1875 to 1895, for four selected stations—namely, San Francisco on the Pacific, Denver and Chicago in the interior, and New York on the Atlantic Coast. San Francisco, being situated near the ocean and in the prevailing westerly winds of the middle latitudes, has a marine climate, the westerly wind usually bringing to that city the temperature, approximately, of the ocean. The range of the temperature of the water is not great, and consequently there is found on the Pacific Coast very even temperature. The range at New York should be greater because of its position farther north, but were the prevailing winds from the Atlantic on the eastern seaboard, the range in temperature would not be materially greater than along the Pacific Coast. Temperature conditions at New York are therefore affected somewhat by the proximity of the ocean, and the range is consequently considerably less than in the interior. Denver, Colo., located at a slightly lower latitude than New York City, has a much greater annual range in temperature, and it is even greater than Chicago, the temperature in the latter city being affected by the great lake that washes its shores, but while its annual range is considerable, it is not as great, as a rule, as that observed on the great plains immediately east of the Rocky Mountains, or on the same parallel of latitude where it approaches close to the Pacific Ocean, but is partly protected from the modifying vapor of the ocean by intervening high mountain ranges.

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[1] Difference between the highest and the lowest temperatures ever recorded.

Monthly Mean Temperatures Along the Same Parallel and Along Different Parallels.—The stations selected for this illustration are the same as those used in Fig. 28, except that Boston has been substituted for New York in the first graph of Fig. 29, and Marquette for Duluth in the second graph of the same figure. The mean monthly temperature at San Francisco under the influence of the air that normally moves from the west north of latitude 30° varies little from month to month, the minimum of 50° occurring in January, and the maximum of 60° in September, which is the time when the water of the Pacific reaches its maximum heat after being exposed to the summer sun. There is a difference of only 10° between the warmest and the coldest months. The maximum temperature is not reached at San Francisco until September. The influence of the Pacific Ocean on the climate of the western coast of the United States during every month of the year is quite apparent; but the high range of mountains near the water's edge prevents this influence from being felt far inland. One needs but to scale the lofty crest of but a single range to pass from a humid air, with small daily and annual ranges of temperature, to an arid atmosphere, with wide ranges.

The curves of the monthly mean temperature of Denver, Chicago, and

Boston, nearly superimposed one upon the other, form a strong contrast to the San Francisco curve, reaching their extremes in January and July. In the second graph of Fig. 29 the four stations selected are fairly well distributed from north to south, and include Marquette, Chicago, Memphis, and New Orleans. Here again the maximum monthly temperatures are reached in July and the minimum in January, there being a direct relation between the monthly curves of the four stations. The lines, however, are much closer together in summer than in winter, the Memphis curve almost touching the New Orleans curve in the month of July. These data bear out the statement previously made in this chapter, that the difference in the annual range in temperature between many stations in the United States is due in larger measure to the differences in the temperatures of winter than to the differences in the temperatures of summer. The figures opposite the name of each city give its mean annual temperature.

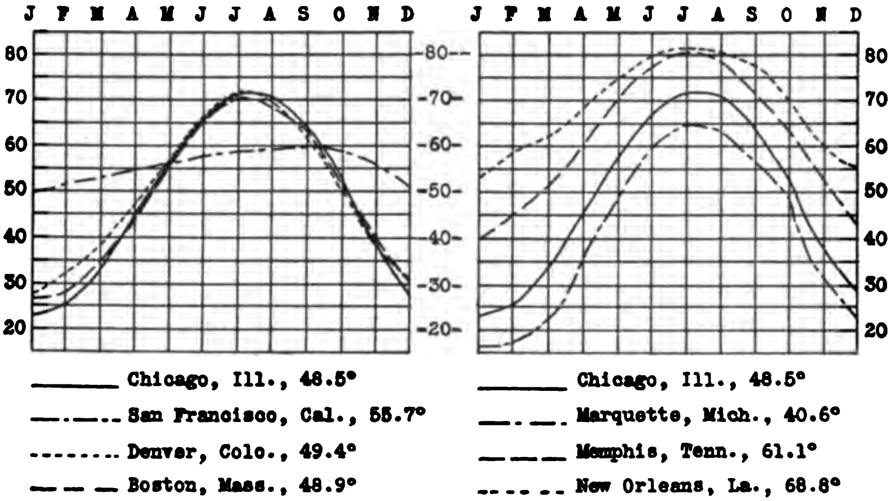

FIG. 29.—MEAN MONTHLY TEMPERATURES.

Fig. 30 shows typical annual temperature curves of different climates. Attention is directed to the difference between marine and continental climates as illustrated by these curves. Compare London and St. Petersburg; the first city, under the influence of the ocean, is cooler in midsummer than St. Petersburg, which lies 8.5° farther north, and is much warmer in winter. Singapore, which is situated but 1.25° north of the equator and in a region where there is but a small land area and a great expanse of water, shows but a trifling variation between any two months of the year.

Frosts; Influence of Soil and Vegetation on Minimum Temperatures.—As previously explained, a given quantity of heat being absorbed by several substances of different specific heats will produce a different temperature in each; the lower the specific heat of a substance the higher will be its temperature; and besides, different substances have different coefficients of absorption and of reflection. Therefore, under the same insolation rocks, clay, vegetation, and other substances come to temperatures that often differ by many degrees.

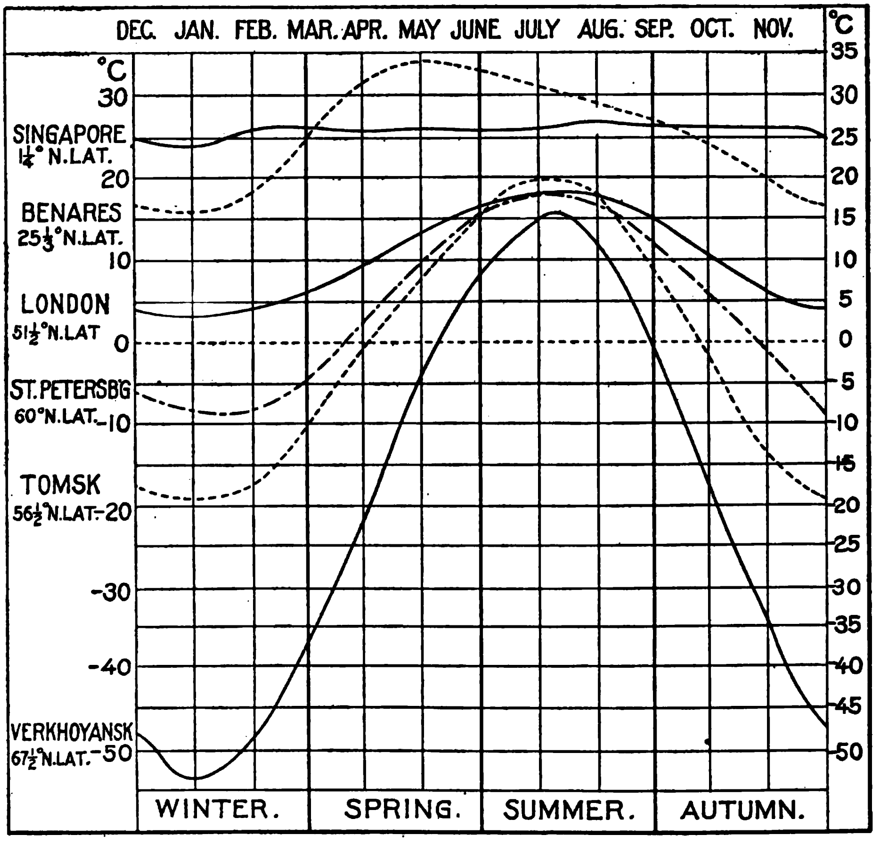

Fig. 30.—Typical Annual Temperature Curves of Different Climates. (After Wagner.)

The air next to earth largely partakes of the temperature of the surface, and, in consequence, when the sky is clear, so that incoming and outgoing radiations may progress freely, and the air is but little disturbed by wind, wide variations in the temperature of a thin stratum of lower air may occur over adjacent plots of ground of *precisely* the same elevation but different covering. These variations have been specially studied with relation to their influence on minimum temperatures at night and the formation of frost.

To be sure, marked differences in minimum and in maximum air temperatures may exist over a surface having a uniform covering, within the area of a single township, or less, as a result of difference in elevation. A ravine or a deep, narrow valley may entrap the air. During clear, cool nights with light wind, frosts will occur in bogs, while in the surrounding uplands the temperature may be from 10° to 20° higher.

But it is not to such anomalies that attention is now directed, but rather to variations in the temperatures of the air that are due to differences in the composition of the surface covering beneath, and in its moisture and heat contents. In 1891–94 the author, in studying the conditions under which frost forms in the cranberry bogs of Wisconsin, was impressed by the fact that the formation of frost on a given field depends more upon the character of the surface and its covering and the degree of heat and moisture to which it has been subjected for the several days preceding than to the general temperature and pressure of the air, one field receiving an injurious frost, another a light frost, and still another none at all, while each field had the same general conditions as to pressure, wind velocity, and direction, and each the same general temperature at a height above its surface of 100 or 200 feet.

When cloudy, rainy, or windy weather prevails there are but slight differences in temperature, but on nights of light wind, high pressure, and clear sky there are often great differences.

Prof. Henry J. Cox, U. S. Weather Bureau, during the three years 1906–08, personally conducted a systematic investigation of the effect of surface coverings and conditions on minimum temperatures and frosts in the same cranberry marshes, from whose report[1] much new and valuable information has been secured for these pages.

How to Protect Marshes Against Frost.—In order to ward off frost, progressive cranberry growers have resorted to three expedients—viz., cultivation, drainage, and sanding. Through cultivation the marsh may be kept clean and free from weeds, moss, or other rank growth, thus permitting the solar radiation to reach the soil and to increase its temperature. The growth of thick vegetation screens the soil from the sun's rays, and there is consequently less heat in such a soil to be given off by radiation or conduction in the nighttime. Drainage lowers the specific heat of the soil and decreases the cooling effect of evaporation; therefore, under sunshine the dry soil becomes warmer than the wet and, whether or not it has *more* heat to give off at night, it has a higher temperature and therefore radiates more freely to the air above. A covering of sand likewise lowers the specific heat of the surface, and thereby conduces to a higher temperature during the day and increased radiation at night. In the Cape Cod cranberry marshes sand about half an inch in depth is spread over the surface of the bog each year, while in Wisconsin no such systematic method has been adopted; but several of the marshes have been sanded from time to time, usually to a depth of about 2 inches, at intervals of several years. These three methods of preventing low night temperatures have been so beneficial that, where systematically carried out, there is practically no need of flooding to prevent frost, except in the spring or autumn.

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[1] To be published as a Bulletin of the U. S. Weather Bureau.

REASONS FOR EXCESSIVELY LOW TEMPERATURES.—The cold air, on nights when frost is imminent, settles gradually down the slopes to the bottom lands, and if all the conditions in these bottom lands or bogs were the same, there would be no differences in air temperatures at the surface; yet it is interesting to see how much the temperature varies at different places in the same bog, and often even when these places are near together. The difference in temperature over these various surfaces disappears often at an elevation of 3 feet, while at the very surfaces there may be a difference of from 5° to 10°. The cold air, as it settles gradually through gravity, overspreads the marsh, but here and there we find warm places and cold places, and still others having an intermediate value. This variation in temperature is due largely to the differences in temperature of the soil or covering. It is as if heaters of varying power were scattered over the bog, giving off heat to the air immediately above, some in greater quantity, others in less. In places where the heater was protected by vegetation and, therefore, not supplied with much fuel the previous day, or where, much heat being supplied, the specific heat of the heater was so great that but little gain in temperature was effected, or where the fuel was consumed in processes other than those of heating, such as evaporation, there is weak radiation at night; at those places the surface air temperatures remain relatively low. Right here it is important that a close distinction be made between the effect on the air of weak radiation and conduction from a surface of great specific heat and moderate temperature and the effect of rapid transference of heat from a good conductor having a surface of low specific heat and high temperature. In the first instance, a moderate amount of heat may be transmitted for a long time without addition to the original quantity; in the second case, comparatively high temperature is transmitted for a short time, which period, however, may be sufficiently long to span the hours at night when frost is liable to occur.

COMPARISON BETWEEN TOWN AND BOG MINIMUM TEMPERATURES AND BETWEEN VARIOUS BOG TEMPERATURES.—The attention of the forecasters of the Weather Bureau was first attracted to the unusual conditions prevailing in the marshes on account of the great contrast between the minimum readings there and at the regular stations of the Weather Bureau. During the months of June, July, August, and September, 1906, a minimum thermometer exposed near the surface of a peat bog at Mather averaged daily 13.2° below the one exposed in the shelter of the Weather Bureau at LaCrosse, about 50 miles west, and on clear, quiet nights the temperature in the moorland often fell 16° to 24° below the city temperature.

Investigations were carried on at Berlin and Cranmoor, as well as at Mather, and the results obtained often showed strong contrast. In these three marshes minimum thermometers were exposed without shelter over the peat bog a few inches above the surface, and in each case second minimums 3 feet above the first. The average readings of the thermometers near the soil for the four months were 46.7° at Cranmoor, 47.4° at Mather, and 50.8° at Berlin. In each marsh the reading of the upper of the two thermometers averaged higher, the differences being as follows: Cranmoor, 6.2°; Mather, 3.1°; and Berlin, 1.5°. On June 3d the instruments at Cranmoor showed a surprising difference of 13°, and at Mather a difference of 9° was recorded on July 7th, while at Berlin a difference of 4° was observed on several days. The reason for the comparatively high temperature near the surface at the Berlin marsh, and the consequent small difference between the readings of the upper and the lower thermometers, is due to the fact that the section where the instruments were exposed had been carefully weeded and cleaned, and was free from moss, which existed at the corresponding locations at Cranmoor and Mather. There was little difference between the readings of the upper and the lower thermometers during cloudy and windy weather.

EFFECT OF SANDING ON THE SURFACE MINIMUM TEMPERATURE.—Additional minimum thermometers were placed in the vines over newly sanded surfaces in the three marshes, the locations selected representing the best results that could be secured from sanding, draining, and cultivating, and comparisons were made between the readings here obtained and the readings close to the surface over the unsanded peat bog. The average night minimum temperature over the sand for the four months was 5.9° higher than over the peat at Cranmoor, 4.2° at Mather, and 1.8° at Berlin. The reason for the slight difference at Berlin was because of the cleaned surface of the bog, as previously stated. On the night of September 30th the minimum over the sanded surface at Cranmoor was 12° higher than over the peat, while at Mather a difference of 9° was recorded on August 27th.

Minimum thermometers were located at eight places on the surface in the Mather marsh, and soil thermometers at a depth of 3 inches, and observations were made from these instruments during August and September. The results are given below in Table XIX for the month of September, and for our purpose four typical stations are selected. The results are valuable as showing the low minimum air temperature at the surface of a covering of great specific heat, where the loss by radiation from the soil is least (column *d*), and conversely the comparatively high minimum air temperature next to a surface of small specific heat and great radiation.

Table XIX.

Average Temperatures for September, 1906, *in the Mather Marsh.*

	(a)	(b)	(c)	(d)
Maximum soil temperature at depth of 3 inches.	64.2°	62.3°	61.1°	59.8°
Minimum soil temperature at depth of 3 inches..	56.1°	59.1°	59.1°	59.2°
Nightly loss of soil temperature	8.1°	3.2°	2.0°	0.6°
Minimum air temperature at surface..........	51.2°	47.9°	44.2°	44.1°

(a) Newly sanded and thinly vined, representing best conditions of sanding, draining, and cultivating.

(b) Newly sanded and heavily vined, representing best conditions of sanding and draining.

(c) Old (9 years) sanded and heavily vined, stratum of peat over old sand.

(d) Uncultivated marsh, peat, and sphagnum moss, poorly drained.

The highest maximum soil temperatures, the lowest minimum soil temperatures, and the highest minimum air temperatures occurred in the sanded sections, bare or thinly vined and well drained; while the lowest maximum soil temperatures, the highest minimum soil temperatures, and the lowest minimum air temperatures were found in the uncultivated marsh which was poorly drained and had a thick growth of vegetation and sphagnum moss.

The curves made by soil thermographs from September 23 to 30, 1906, are reproduced in Fig. 31. The great range in temperature in the newly sanded and thinly vined section, as compared with that in the peat bog with moss, is graphically shown, while the temperature in the newly sanded and heavily vined section has an intermediate value.

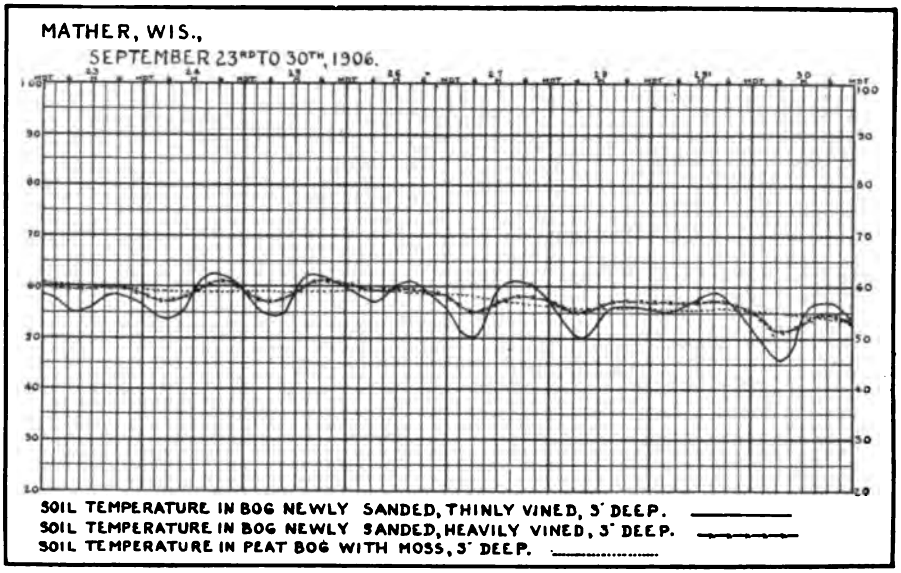

Fig. 31.—Soil Temperature in Bogs.

One soil thermograph was located in the reservoir so as to secure a continuous record of the water temperature 6 inches below the surface, while an air thermograph was placed in a shelter over the bog, 5 inches above the surface. In Fig. 32 are found the curves of these two instruments and also the curve of the soil temperature in the peat bog and moss. Here we have interesting illustrations of the daily variation of the temperature in three elements—earth, water, and air.

It is apparent that sanding, draining, and cultivating are remarkable in their effects on night surface air temperatures.

Minimum Air Temperatures Over Sand and Over Peat at Different Elevations.—Readings were made during the season of 1906, at the Berlin marsh, at two locations about 30 feet apart, one in a peat section that had been carefully cleaned and weeded, and the other in a newly sanded section. Minimum thermometers were placed immediately at the surface and upon posts at elevations of 3 feet. The results for the month of September, 1906, are given in Table XX:

TABLE XX.

Average Minimum Air Temperatures.

	Sanded Section.	Peat Section.
Surface	53.3°	50.0°
Three feet	48.2°	48.0°

The mean temperature at the surface of the sanded section was 3.3° higher than over the surface of the peat; while at the height of 3 feet the difference was only 0.2°—showing that the heat effect of the sanded surface is almost lost at an elevation of 3 feet.

MINIMUM TEMPERATURES OVER WELL-DRAINED AND POORLY DRAINED SECTIONS.—During the month of September, 1906, a comparison of the minimum air temperature readings at the surface between a well-drained and a poorly drained section shows that there was a higher average by 2.8° at the surface of the well-drained and comparatively dry section,

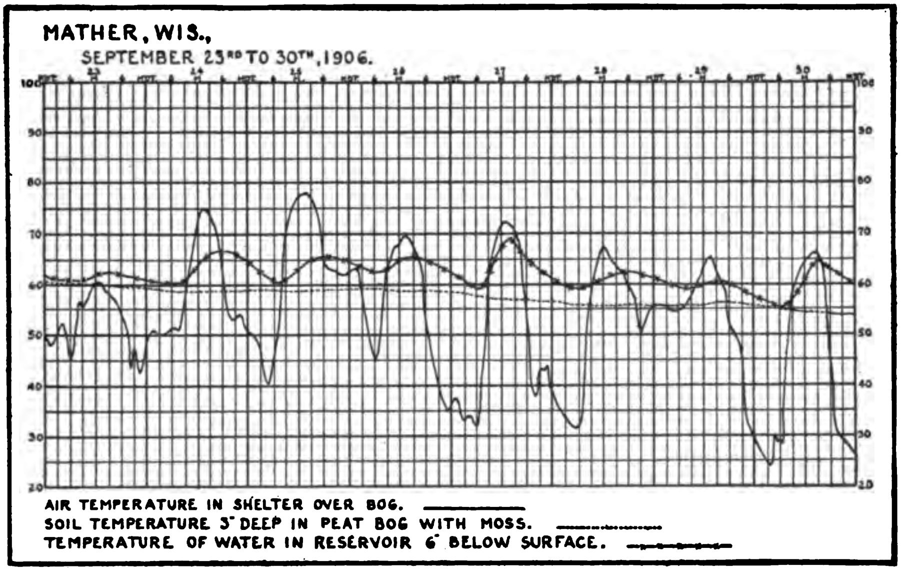

FIG. 32.—AIR, SOIL, AND WATER TEMPERATURE IN BOGS.

this averaging 53.3°, while the average of the poorly drained was 50.5°. An unusually great difference was observed on October 1st, when a killing frost generally froze unpicked berries where flooding was not done. The berries in the poorly drained sanded sections were badly frozen, and a minimum of 27.3° was observed, while in the drier section the berries were unharmed, and the lowest temperature was 35.8°.

Effect of the Cold Soil of Spring on Frost.—Throughout the investigation Professor Cox was impressed with the fact that the temperature of the soil is a most important factor in the control of night air temperature in the bogs. Frosts occur in the bogs in May and even in June under atmospheric conditions that would not produce frost in the midsummer months, due to the fact that the soil is much colder in the spring and early summer than in midsummer.

Reflowing Marshes to Ward Off Frost.—All the marshes of Wisconsin are flowed each year in the late fall, the flood being kept over the bog at a depth of several inches until late in the spring, and water is available for reflowing the bog during the crop season as a protection against frost. Heavy rains often answer the same purpose as flooding. For instance, on July 28, 1906, rain flooded the marsh at Berlin, and, as a result, the minimum temperature of the following night was 22° higher than at the Cranmoor marsh, where the rain had not been sufficient to flood.

Relations Between Dew-point and Ensuing Minimum Temperature.—Cox's investigations show that observations of dew-point in the early evening are worthless in estimating the probable minimum temperature during the ensuing night. While such observations in uplands and comparatively dry sections of the country may be of some service, it was found that in the bogs no relation whatever existed between the dew-point and the subsequent minimum temperature. At Mather, during the season of 1906, the minimum temperature averaged 8.2° lower than the dew-point observed the previous evening, and in extreme cases there was a difference of 20° and 22°. At the Berlin marsh, on the night of September 27th, at 11 P.M., the dew-point was found to be 43° near the edge of the bog, 1° below the temperature in the shelter; yet frost began to form in portions of the marsh at 1 A.M., when the temperature had fallen to 28°; the frost became general about 2 A.M., and the following morning a minimum of 24.4° was observed.

Effect of Fog on Minimum Temperatures.—Fog almost invariably overspreads the moorlands when the temperature falls rapidly after a warm day, the cool air settling and coming in contact with the warm, moist ground. It is not a fact, however, as many suppose, that fog thus formed protects the marsh from frost, unless the fog becomes dense. It is, of course, a factor, and decreases the fall in temperature. The temperature often continues to fall in the moorlands on nights of fog in spite of the enormous amount of heat liberated in the formation of the fog.

On the night of September 23d–24th, at Berlin, special observations were made. The marsh was wet from recent rains, the water being practically up to the surface. About 7 P.M. fog was visible, gradually overspreading the marsh, and by 3 A.M. it was dense. The whole marsh seemed to be reeking with moisture, and the relative humidity was 100 per cent continually during the night after 10 P.M.; yet the temperature fell rather uniformly until 4 A.M.; then it continued stationary until 5 A.M., after which it rose gradually. Frost was observed in the morning on the wooden car tracks, and it was pronounced on those farthest from the ditches. The thermometer placed upon the wooden tracks registered 27°.

In this case it is probable that had there been no rain and flooding there would have been a destructive frost on the berries and no fog.

Horizontal Distribution of Temperature.—The temperature as actually observed on the uneven surface of the earth, if shown graphically by means of isotherms, would require a multiplicity of lines. It is, therefore, well to reduce the observations to some common level before attempting to combine them in a representation of the horizontal distribution of temperature. The vertical gradient varies with local peculiarities of the topography and with the season of the year. A uniform correction for elevation for all places and seasons is therefore only an approximation.

On Charts Nos. 1, 2, and 3 (after Buchan) the attempt has been made to represent the average horizontal distribution of temperature for the year and for January and July, as it would appear if all the stations whose temperature records have been considered were at sea level. To accomplish this the temperatures of land stations have been increased by 1° C. for each 150 meters of elevation, or 1° F. for each 270 feet of elevation, and one is able to compute from the chart the actual temperature of a place whose elevation is known.[1]

The isotherms of Chart No. 1 show the annual sea-level temperatures for the globe. It will be noted that the areas of highest temperature lie north of the equator in India, Central Africa, and Mexico.

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[1] When reference is made to the temperature of a specific station the actual temperature, uncorrected for elevation, will be given.

TABLE XXI.

Mean Air Temperature Distribution in Latitude.[1]

LATITUDE.	Percentage of Land Surface.	Mean Annual Temperature.	January.	July.	Difference.
N. 90°	..	(−4.0)	(−36.4)	(32.0)	68.4
80°	24	+1.6	−30.9	32.4	63.3
70°	54	13.7	−15.7	44.1	59.8
60°	64	29.8	+3.9	56.9	53.0
50°	55	42.5	19.9	64.6	44.7
40°	47	57.1	42.9	75.4	32.5
30°	42	68.4	59.5	81.0	21.5
20°	32	76.9	71.7	82.4	10.7
10°	24	80.8	78.5	80.7	2.2
Equator	23	79.9	80.0	78.2	1.8
S. 10°	23	78.2	80.0	74.9	5.1
20°	23	73.9	77.6	66.9	10.7
30°	18	64.9	70.0	57.1	12.9
40°	5	54.0	59.1	46.9	12.2
50°	2	41.5	47.4	36.8	10.6
60°	1	(30.0)	34.9	(25.2)	9.7
Northern hemisphere		59.4	46.4	72.5	26.1
Southern hemisphere		58.8	63.5	54.3	9.2
Earth as a whole		59.0	54.9	63.3	8.4

Charts 2 and 3 show the sea-level distribution of temperature for January and July, respectively. In January there are warm areas over the continents in the southern hemisphere, and excessively cold areas over the land masses in high latitudes in the northern hemisphere, the coldest area overlying Siberia. In July the northern land areas are warm, but the charts do not show cold areas in the southern hemisphere corresponding to those in Siberia and North America in January. Table XXI shows that the northern hemisphere averages 9° warmer in July than does the southern hemisphere in January, and 7.9° colder in January than does the southern hemisphere in July. Also, that while the difference between January and July mean temperatures for the northern hemisphere is 26.1°, in the southern hemisphere it is only 9.2°.

COMPARISON BETWEEN MARINE AND CONTINENTAL MEAN AIR TEMPERATURES.—Comparison between the mean temperatures along the meridians 120° E., which passes mainly over land, and 20° W., which extends principally over oceans, in the northern hemisphere, is made in Table XXII, which follows:

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[1] Adapted from Batchelder's tables, in *The American Meteorological Journal,* vol. x, pp. 460–463.

TABLE XXII.

Mean Air Temperature.[1]

LATITUDE. N.	ANNUAL.		JANUARY.		JULY.	
	Long. 120° E. Land.	Long. 20° W. Water.	Long. 120° E. Land.	Long. 20° W. Water.	Long. 120° E. Land.	Long. 20° W. Water.
80°	−3°	8°	−28°	−27°	31°	34°
70°	0°	28°	−47°	13°	50°	40°
60°	20°	44°	−29°	38°	70°	53°
50°	36°	54°	−8°	49°	75°	60°
40°	51°	63°	15°	59°	78°	71°
30°	63°	70°	42°	64°	84°	74°
20°	75°	74°	68°	71°	82°	78°
10°	81°	79°	78°	77°	81°	80°
0°	82°	79°	80°	81°	80°	78°
Mean...	45.0°	55.4°	19.0°	47.2°	70.1°	63.1°

Spitaler has computed that the temperature of all land and of all water hemispheres would be as follows:

TABLE XXIII.

	Water Hemisphere.	Land Hemisphere.	Difference.
Temperature at the equator........................	72.0	106.7	+34.7
Temperature at the pole............................	14.9	−19.8	−34.7
Temperature of the whole hemisphere...............	56.8	68.4	+11.6

THERMAL ANOMALIES.—If the mean January and July temperatures of each parallel of latitude, as given in Table XXI, are subtracted respectively from the temperatures shown on Charts 2 and 3 for these same parallels, the remainders will give the thermal anomalies along the parallels, as shown on Charts 4 and 5. The greatest thermal anomaly, + 40°, occurs over the North Atlantic Ocean in January. In July the greatest thermal anomaly is + 20°, and it occurs over the northwestern part of the United States. As examples of variations in temperature along a parallel we may note that in January the average temperature for Thorshaven is + 38°, for Yakutsk, Siberia, —45°, and for Dawson, Canada, —24°, all three stations being on about the same parallel of latitude. The corresponding July temperatures are: For Thorshaven, 51°; for Yakutsk, 66°; and for Dawson, 60°. Red Bluff and Fresno, California, have an average July temperature of 82°, while at Point Reyes, on the Pacific coast of the same State, the corresponding temperature is 54°.

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[1] Samuel F. Batchelder, in *American Meteorological Journal*, vol. x, pp. 460–463.

The temperature anomalies in the southern hemisphere are nowhere greatly in excess of 10°.

ABSOLUTE EXTREMES OF TEMPERATURE.—The highest temperatures occur in northern Africa, in the interior of Australia, in southwestern Asia, and in southwestern North America. Ouargla, Algeria, has a record of 127.4° on July 17, 1879; Jacobadad, India, 126.0° on June 13, 1897; while Mammoth Tank, California, has a record of 128° in June, 1887.

The minimum temperatures of Siberia and North America are much lower than any that have been observed in the southern hemisphere. Hann states that the lowest temperature ever observed was —90.4° at Verkhoyansk, in Siberia. The lowest temperature ever recorded in the United States was —63.1°, at Poplar River, Montana, the elevation of the station being 2,030 feet. At Cape Adair the lowest temperature recorded during the year the station was in operation was —43.1° in August. The lowest temperature recorded in the Antarctic by Shackleton was —57° on August 14, 1908.

BIBLIOGRAPHY

HANN, J., "Handbuch der Klimatologie," 3d ed., v. 1, Stuttgart, 1908.

HANN, J., "Handbook of Climatology," 2d ed., Pt. I, translated by R. DeC. Ward, New York, 1903.

HANN, J., "Lehrbuch der Meteorologie," 2d ed., Leipzig, 1906.

ON THE ECONOMIC EFFECTS OF EXTREME TEMPERATURES

GARRIOTT, E. B., "Notes on Frost," Revised ed., Washington, 1908. (United States Department of Agriculture, *Farmers' Bulletin* 104.)

McADIE, ALEXANDER G., "Frost Fighting," Washington, 1900. (United States Weather Bureau, *Bulletin 29*.)

WILLIAMS, H. E., "Temperatures Injurious to Food Products in Storage and During Transportation, and Methods of Protection from the Same," Revised ed., Washington, 1896. (United States Weather Bureau, *Bulletin 13*.)

CHAPTER VIII

THE ISOTHERMAL LAYER

THIS chapter is an adaptation of an article by Prof. W. J. Humphreys,[1] of the U. S. Weather Bureau, on the vertical temperature gradients of the atmosphere. Here no effort will be made to give detailed readings at fixed elevations, such as are found in Chapter VII, but a general survey of the observations will be presented together with an explanatory theory that will serve the useful purpose of binding all the phenomena into one connected whole.

Balloon Records.—During the past ten years hundreds of sounding balloons, equipped with suitable registering apparatus, have been sent up under widely different conditions to various heights; many to 15 kilometers, some to 20 kilometers, and a few to elevations approximating 30 kilometers. The records represent flights by day and by night made in all sorts of weather and in every season of the year; flights over continental, island, and ocean regions; and flights at different latitudes from the equator to beyond the Arctic Circle; and, besides, the apparatus used has been constructed by several makers and according to different designs. In this way disturbances due to location and to storm influence have been detected, and systematic instrumental errors largely avoided. But the results of all the observations are in general accord, and show that the explored portion of the atmosphere consists of three more or less distinct regions.

THE ATMOSPHERE VIEWED AS IN THREE LAYERS:

I. The region of terrestrial disturbance, extending from the ground to an elevation of, roughly, 3,000 meters above its surface, in which the temperature gradient usually is very irregular and often locally reversed. This is the region most affected by strong convection, and is the principal seat of the over- and the underrunning of warm and of cold currents. It is, therefore, distinctly the storm layer.

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[1] *Bulletin of the Mount Weather Observatory*, vol. ii, No. 1. *Astrophysical Journal*, January, 1909.

With clear weather, especially in the summer time, the temperature gradient of its lower portion—that is, the portion next the surface of the earth—is apt to be quite steep, showing rapid decrease of temperature with elevation, approaching the adiabatic during the heat of the day, and a rapid increase during the early morning—the morning inversion. When, however, the air is moist, and heavy clouds are formed, this phenomenon is absent; the temperature then generally falls from the ground to the under surface of the clouds, an elevation usually between 500 and 1,500 meters, at one rate, and through them at another, but in both places at a rate greatly below the adiabatic either of dry or of unsaturated air. Within the cloud, especially if it is of the nimbus type, much heat is set free by the process of condensation, and this not only helps to keep up the temperature of the cloud itself, but by radiation sends heat to the lower atmosphere and to the earth.

II. The region of uniform changes, lying roughly between the upper limits of region No. I and the 10,000-meter level above the sea, in which the temperature gradient, nearly constant, approaches the adiabatic. This region, with a temperature always much below the freezing point, is comparatively free from condensation and precipitation—that is, it lies above the average nimbus cloud, while the cirri float in only its topmost portion. During storms it may be the seat of vertical convections of varying extents and intensities, but its normal condition is one of stability, as shown by its usual freedom from clouds.

III. The region of permanent inversion, or all that explored portion above the 10,000-meter level or thereabouts. Here the temperature is nearly uniform, though it generally increases slowly with ascent; in other words, the temperature gradient is small and usually positive, and vertical convection therefore always impossible.

In the region of terrestrial disturbance—that is, in the lower or denser portions of the atmosphere—the winds are irregular, being chiefly determined by the locations and intensities of cyclones and anticyclones. (See Chapter IX.) These also influence the movements of the air far up in the region of uniform changes, but are less and less effective as the elevation is increased. In the upper portion of the second region the great planetary circulation (Chapter IX) mainly prevails, as shown by the movements of the cirrus clouds, which are near its upper limit. It is known, from the drifting of balloons, and from observations on clouds, that in this region the wind moves faster and faster with increase in elevation, and easterly in extratropical countries.

Above the inversion level—that is, in the third region—the velocities of the winds are much less [1] than they are immediately below it. On passing up from the one region into the other this velocity is usually found to drop by from 25 to 80 per cent, and apparently the directions in the two regions have but little interdependence. Besides, the air above the place of inversion seems always to be excessively dry,[2] no matter what the humidity may be at lower levels.

The height, generally sharply defined, of the place where the upper inversion begins, and its temperature, are functions of season, of latitude, of barometric pressure, and probably of still other conditions. It is high up in a well-formed anticyclone and correspondingly low in a cyclone. It is at greater elevations and higher temperatures in summer than in winter, and descends with increase of latitude from the tropics to the polar regions. The higher it is found above the earth the lower in general is its temperature, and conversely the lower it lies, season and other things being equal, the warmer it is.

THE ATMOSPHERE DIVIDED INTO TWO LAYERS THAT INTERMINGLE BUT SLIGHTLY.—We therefore have two distinct strata in our atmosphere that intermingle but slightly: a lower or inner turbulent one, which includes the first two regions previously described, with a large negative temperature gradient, and an upper or outer one, with a small positive gradient, floating on the first like oil on water. The lower stratum contains from two thirds to three fourths of the entire mass of such gases of the air as oxygen, nitrogen, and all the members, except helium, presumably, of the argon family; a still greater proportion of the carbon dioxide, and nearly all the water vapor. It is warm in its lowest portion, but cools, irregularly at first, then rapidly and nearly regularly, with increasing elevation to a minimum of from —40° C. to —70° C. The upper stratum contains extremely little water vapor, and its temperature rises, sometimes abruptly at the start and then slowly, but usually slowly all the way, with elevation from the place of inversion to an unknown temperature at a height not yet reached. Occasional observations indicate an isothermal condition, and for this reason the outer atmosphere is often called the *isothermal layer*,[3] and a few observations have shown even a slow cooling with elevation, but both these conditions are unusual.

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[1] Bassus, *Beiträge zur Phys. der freien Atmos.*, vol. ii, p. 92, 1908.

[2] Kleinschmidt, *Beiträge zur Phys. der freien Atmos.*, vol. ii, p. 205, 1908.

[3] Stratum at constant temperature.

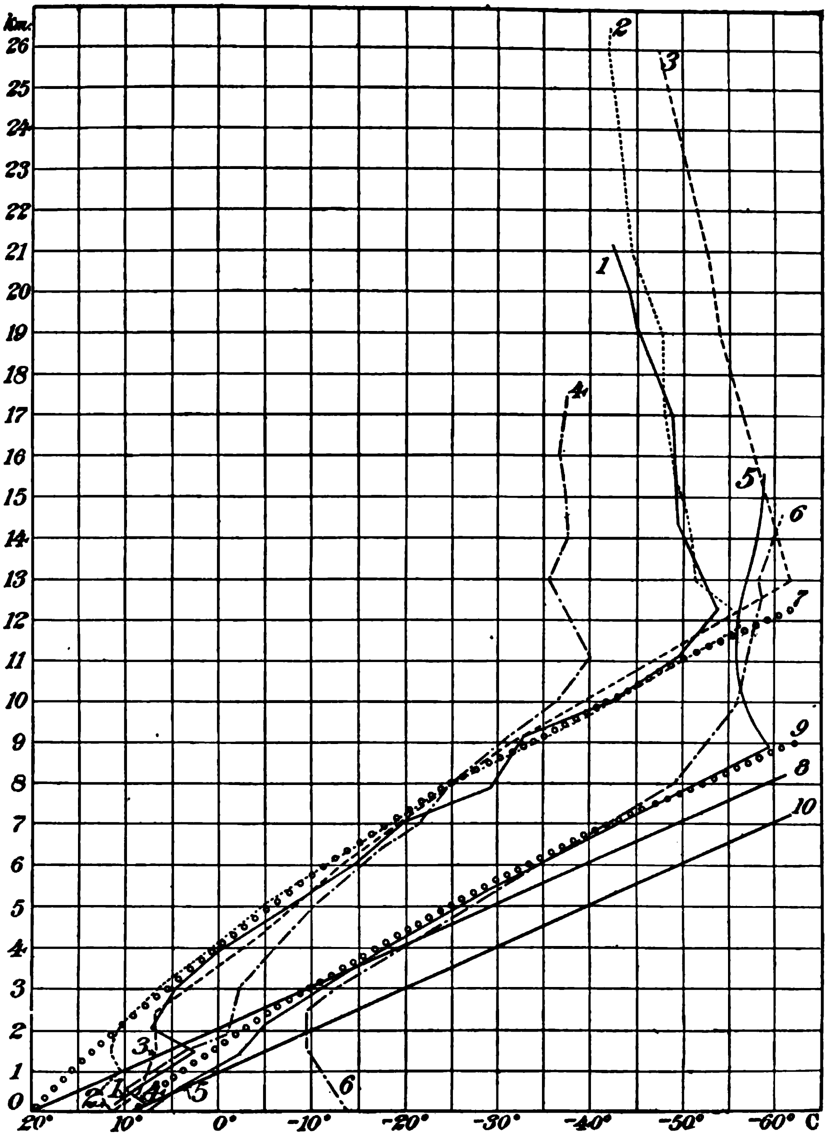

FIG. 33.—VERTICAL TEMPERATURE GRADIENT CURVES EXTENDING INTO ISOTHERMAL LAYER.

The region above the upper inversion cannot appreciably be penetrated by convection currents from the air below, since this would cause a cooling by expansion of the rising mass to a temperature lower than that of the surrounding medium, so that under the same pressure or at the same level its density would be greater than that of the adjacent air; and therefore all storms, all condensation, all abnormal and irregular moisture distribution, and virtually all dust, except that of meteors and of violent volcanic eruptions, are limited to the lower atmosphere.

The upper atmosphere, floating on the lower, will rise and fall as a whole with the latter. Upward currents of air, when they reach the inversion surface, since, as explained, they cannot rise any farther, are forced to spread out under it somewhat as warm air in a room spreads out next the ceiling; and doubtless this air carries with it the moisture for the highest cirrus clouds because, like the inversion layer, they approach nearer the earth in colder regions, nearer in winter than in summer, and are highest toward the end of a clear, warm spell of weather.

Much of the foregoing is illustrated by the temperature gradient curves of Fig. 33.[1]

Curve 8, a straight line, gives the adiabatic gradient for dry air and Curve 7 gives the temperature gradient for saturated air, both starting at sea level with a temperature of 20° C. Curves 9 and 10 are the same as 7 and 8 respectively, except that the initial temperature is assumed to be 9° C. Curves 1 to 3, inclusive, give a summer group, while 5 and 6 represent winter gradients. It will be noticed at once, and this is generally true, that the winter curves have a slope intermediate between the dry adiabatic and those of summer, and that the temperature gradient in the region of uniform changes, or from 3 to 8 or 9 kilometers, is distinctly less in summer than it is in winter. It will also be noticed that the upper inversion is located higher in the summer than in the winter, and that a cyclonic condition, or low barometer, Curves 4 and 5, lowers the place of inversion. The place of inversion, usually, and in all these curves except No. 6, is rather sharply defined.

Departure of Gradient from the Dry Adiabatic.—The average temperature gradient, even in the region of uniform changes where the gradient is greatest, is less than the adiabatic of dry air; due partly to the heat it absorbs in the form of terrestrial and solar radiations—an amount that during the day is in excess of the loss—but chiefly to the fact that the air is not dry, and that it therefore receives much heat, as it rises, from condensation of the moisture it contains. This liberated sensible heat, by all processes of distribution—conduction, convection, and radiation—extends to and warms the colder masses above, and decreases by counter radiation the loss of heat from lower levels. The temperature gradients are modified most in the lower atmosphere, where the average percentage of saturation is greatest, and where, because of the temperature, its water capacity is relatively large.

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[1] This figure is copied, with slight additions—i. e., curves 7 to 10, inclusive—from the *Annuaire Météorologique pour* 1908, Observatoire Royal de Belgique. The flights giving the data on which these curves are based are reported in detail by Hoormann in *Ciel et Terre.*

Curves 7 and 9 show how closely the actual normal gradients follow saturation paths, even though actual saturation seldom exists except in the midst of clouds, and how widely they depart from lines 8 and 10, that correspond to dry adiabatic expansion.

Seasonal Differences in Temperature Gradient.—The conditions that determine the departure of ordinary air gradients from those of dry air, insolation, and moisture content, are more pronounced in the summer than in the winter, and therefore summer gradients in the region of uniform changes and above the surface turmoil should differ from winter ones in being still farther removed, as they actually are, from the adiabatic curve of dry air.

Storm Gradients.—A summer cyclone furnishes the extreme of departure from dry-air conditions, and therefore also yields the extreme gradient departure from the dry adiabatic, as illustrated by Curve 4. It sets free much heat by the condensation of moisture drawn in by the winds from distant regions. Two centimeters of rain, for instance, will free as much heat as the surface of the earth would receive in sixteen clear summer noon hours of sunshine; and practically all this heat goes to the higher atmosphere, as the lower levels and the ground are not warmed by the rainfall, but rather cooled by its evaporation and often by the underrunning of masses of cold air. The upper and the lower parts of Curve 4 illustrate these effects.

Cause of the Upper Inversion.—In accordance with the theory of Humphreys,[1] and also that of Gold,[2] the causes of the upper inversion are to be found in the phenomena of absorption and of radiation of heat as they pertain to the substances concerned and to the particular limits of wavelength and of temperature involved. An adequate discussion of this theory would be somewhat out of place in a book on descriptive meteorology, and therefore cannot be given here. However, the student is recommended to consult these and other original papers on this important subject.

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[1] See papers in *Mount Weather Bulletin*, vol. ii.

[2] *Proceedings Royal Society*, Series A, vol. lxxxii, p. 43.

Cause of Abrupt Change of Temperature Gradient.—The sharp definition of the place of inversion probably is due to the existence at that level of a more or less well-formed cloud veil, which becomes to that extent the locus of insolation. If so, then a sky with extensive cirrus clouds should give immediately above the inversion—presumably the upper surface of the cirrus—a rapid increase of temperature with elevation, while a serene sky should furnish a curve of gradual transition from the one gradient to the other. Both these conditions and results are shown by the curves, which are in harmony with other flights under similar circumstances. No. 2 shows the effect of cirrus clouds, and No. 6 the gradient when the sky is perfectly clear. In the one the increase is sudden and large; in the other it is gradual. Doubtless, too, the arrest of pronounced vertical convection often plays an important part in this phenomenon.

Cause of Seasonal Difference in Height of Inversion.—During the summer the moisture content of the air, because of increased temperatures, is greater than it is in winter, and extends to greater elevations, and therefore the effective radiating surface is correspondingly elevated. This, combined with the difference in the gradients for the two seasons—less in summer than in winter—puts the inversion level at its greatest elevation during the warmer weather.

Cause of Seasonal Difference in Temperature at Inversion Surface.—The lower atmosphere and the surface of the earth receive more insolation during the summer than in the winter, and consequently must radiate more at this season. Therefore, if the inversion temperature is determined mainly, or even largely, by earth radiation, it should be greatest in summer and least in winter; and this is supported by the published observations from Trappes, from Uccle, and from Strassburg, and presumably, therefore, is generally true.

Cause of Latitude Effect on Height of Inversion.—Change in latitude at any given season is analogous, meteorologically, to change of season at any given latitude, and might be expected to lead, as it does, to a corresponding change in the height of the inversion.

Cause of Relation Between Barometric Pressure and Height of Inversion.—Normally the region of high barometer is one of clear weather, while a low barometer is accompanied by precipitation, which correspondingly heats the upper air, and decreases its temperature gradient. As a result of this heating the place of inversion is one of lower level and higher temperature, as is well illustrated by Curve 4.

BIBLIOGRAPHY

The latest and fullest summary of our present knowledge of the upper atmosphere is the report by E. Gold and W. A. Harwood, presented at the Winnipeg, 1909, meeting of the British Association for the Advancement of Science, " The Present State of our Knowledge of the Upper Atmosphere as Obtained by the Use of Kites, Balloons, and Pilot Balloons." This report was distributed in pamphlet form at the Winnipeg meeting, and will presumably appear in the general report of that meeting.

The voluminous literature on the isothermal layer is scattered through recent volumes of the meteorological and physical journals, especially *Beiträge zur Physik der freien Atmosphäre,* Leipzig; *Meteorologische Zeitschrift,* Braunschweig; *Ciel et terre,* Bruxelles; *Quarterly Journal of the Royal Meteorological Society,* London; *Comptes Rendus Hebdomadaires de l'Académie des Sciences,* Paris; *Nature,* London; and *Monthly Weather Review,* Washington.

The temperature data obtained in the whole series of international sounding-balloon observations are very fully discussed in a memoir published by Dr. Arthur Wagner in *Beiträge zur Physik der freien Atmosphäre,* Bd. iii, Hft. 2 and 3 (Leipzig, 1909). This publication came to hand too late to be utilized in the preparation of the foregoing chapter.

CHAPTER IX

ATMOSPHERIC PRESSURE AND CIRCULATION

ATMOSPHERIC PRESSURE

Gas Pressure.—The attraction of gravity on the gases of the atmosphere causes them to exert a pressure on the surface of the earth. The actual pressure at any given place is directly due to the elastic pressure (molecular bombardment) of the gases present, and is distributed among them according to their volume percentages at that particular place, but the sum total of these several partial pressures per unit area in the open atmosphere, as measured by the barometer, is always just equal to the combined weight of all the gases in a vertical column of unit cross section directly above this area.

The circulation of the atmosphere, and, therefore, to a great extent the precipitation, are intimately related to the pressure distribution.

The average pressure at sea level is about 14.7 pounds per square inch. The reason that ordinarily this pressure is hardly noticeable is that it is exerted on all sides of a body, and generally on the inside as well as on the outside. If we remove the air from the inside of a glass vessel by means of the air pump or otherwise, then the external pressure becomes at once apparent.

Mercurial Barometer.—Torricelli, a pupil of Galileo, was one of the earliest investigators to demonstrate that the atmosphere exerts pressure. He also discovered the principle of the mercurial barometer, which is now universally employed to measure this pressure. His experiment, performed as early as 1643, consisted in filling with mercury a long glass tube sealed at one end. The tube was then inverted and the open end immersed in a cup of mercury. The mercury in the tube no longer completely filled it, neither did it all run out; but the top of the mercurial column came to rest at a point about 30 inches above the level of the mercury in the cup. Since there was no air in the tube to press downward on the mercurial column, the weight of the mercury in the tube was just balanced by the weight of

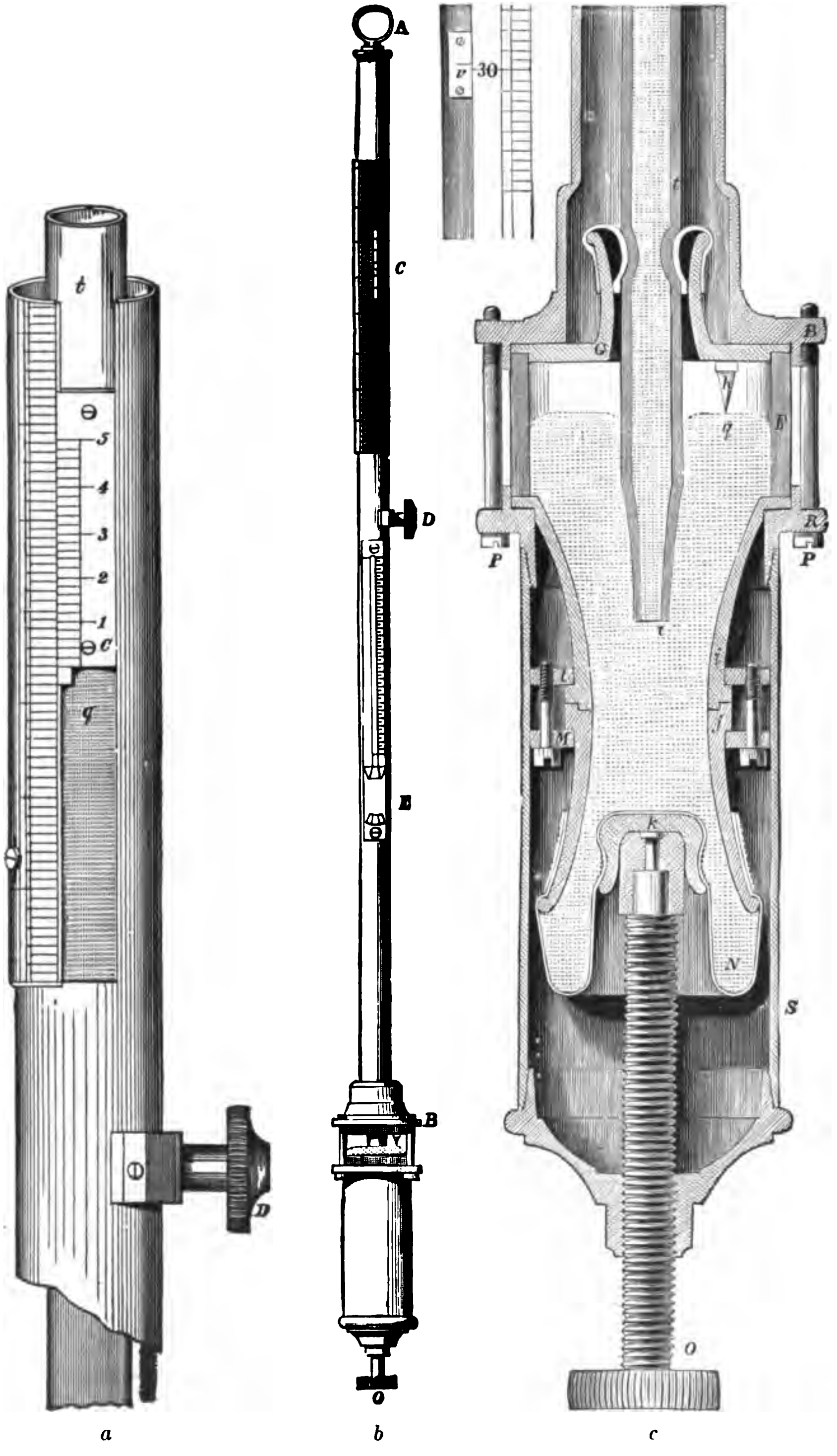

FIG. 34.—THE MERCURIAL BAROMETER.

a column of air having at the cup the same cross section as the mercurial column, and extending from the surface of the mercury in the cup upward and slowly expanding along the lines of gravity to the outer limit of the atmosphere. The density of mercury at a temperature of 32° F. is about 0.4906 pounds per cubic inch. The total pressure of the atmosphere in units of weight when the barometer stands at 30 inches and the thermometer at 32° F., is therefore found by the equation $W = 30 \times 0.4906 = 14.72$ pounds per square inch, or 2120 pounds per square foot.

Since atmospheric pressure is usually determined by measuring the height of a mercurial column it is customary to express the pressure in inches or millimeters of mercury rather than in units of pressure or of force.

The mercurial barometer is simply Torricelli's mercury-filled tube and cup, with a conveniently arranged scale for measuring the height of the mercurial column in the tube. There are many different forms of the barometer, however, owing principally to variations in the form of the cup, or cistern, as it is ordinarily called, and in the arrangement of the scale. A common form is that shown in Fig. 34*b*, which is known as the Fortin barometer. The feature of this barometer is the adjustable cistern, shown in detail in Fig. 34*c*. The bottom of the cistern is a leather bag supported on the plunger *k*, that may be raised or lowered by turning the screw *o*. By this means the surface of the mercury in the cistern may be made to just touch the ivory point *h*, the lower end of which is the zero of the barometer scale. The glass tube *t* is inclosed in a metal case with two large openings opposite to each other, through which the top of the mercurial column may be seen. The upper end of the barometer scale is engraved at the side of one of these openings, as shown at *C*, Fig. 34*b*, and in greater detail in Fig. 34*a*. A vernier, also shown at *C*, is moved up or down this opening by means of a rack and pinion, until its lower edge appears to just touch the top of the mercurial column. The position on the scale of the lower line of the vernier gives the distance from the top of the mercury in the cistern to the top of the mercurial column in the tube, or *the height of the barometer* when vertical.

BAROMETRIC CORRECTIONS.—Several corrections must be applied to this *observed reading* of the barometer before it will give the true air pressure. (1) Since the mercury and also the metal scale expand with heat it is necessary so to change the reading as to give the height of the mercury at some standard temperature, usually 32° F. (2) Since the mercury does not wet the glass, the outer edge of the mercurial column is depressed, giving a curvature to the top of the column called the *meniscus*. In small tubes the entire column will be somewhat depressed, but if care is taken before reading to first lower and then raise the mercury in the cistern the meniscus will always have the same form and the amount of the depression of the center of the column will be practically constant. (3) The barometer scale may be in error by a fixed amount. The combined effect of (2) and (3) is usually determined by comparison with a standard barometer of known accuracy. (4) Since the apparent local force of gravity varies with latitude and altitude, therefore at sea level at the poles a given height of the barometer indicates a greater pressure than it does at sea level at the equator, or than it does at an elevation above sea level. It is therefore customary to correct barometer readings to what they would have been with the force of gravity the same as at sea level at latitude 45°. Corrections (2), (3), and (4) are usually combined into one and called the instrumental correction. There are also corrections for imperfect vacuum in the tube, impure mercury, and departure from verticality, which are of only minor importance in well-installed and properly constructed instruments. After applying all the above corrections to the *observed* barometer readings, the *actual* barometric pressure of the station is obtained to a close approximation.

When barometer readings from several stations are to be compared it is necessary to reduce them to what they would be if the stations all had a common level. Usually they are reduced to what they would read at sea level by adding to each the inches of mercury equivalent in weight to the column of air between the barometer cistern and sea level. The pressure thus determined is called the *sea-level pressure* of the station, and this is the pressure usually entered on weather charts.

Aneroid Barometer.—Besides mercurial barometers, aneroid barometers are also employed, particularly as portable instruments. In these the force of atmospheric pressure is balanced against the force of elasticity in a heavy steel spring. A common form of aneroid is shown in Fig. 35. From a short metal cylinder or cell *M*, with thin corrugated ends, the air is nearly exhausted. The tendency of the external pressure to press in the ends of this cell is counteracted by the elastic force of the heavy steel spring *R*. Variations in pressure will cause slight movements in the ends of the cell and of the spring, which movements are communicated by means of a system of levers to the index finger *a*, and at the same time greatly magnified. A suitably graduated dial, not shown in the figure, is placed under this index finger, so that the pressure may be read off at once.

Since an increase of temperature weakens the elastic force of the spring, a small quantity of air is left in the cell, the expansive force of which with rise in temperature is expected to compensate for the weakening of the spring. In general it will be found, however, that a small correction for temperature effect must be applied to the readings of aneroids. No correction is required for variations in the force of gravity. When subjected to sudden changes of pressure of considerable magnitude, as when placed under the air pump, or when carried up by a balloon or kite, or on a high mountain, aneroids usually require considerable time for all the parts to adjust themselves to the new conditions. The readings during the first few minutes, or in some cases even during the first few hours after the change in pressure has occurred, are therefore apt to be unreliable. .

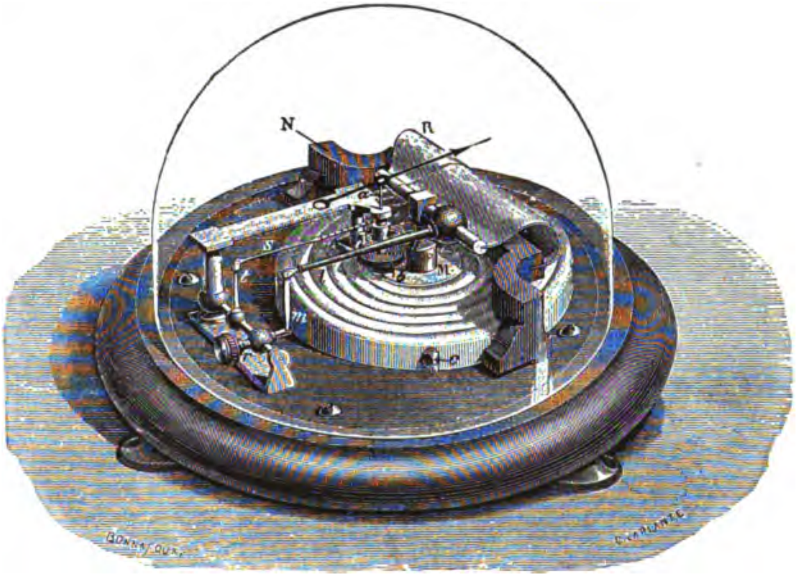

FIG. 35.—ANEROID BAROMETER.

Barographs.—In Fig. 36 is shown a form of aneroid barograph very generally employed to obtain continuous records of the pressure. Instead of one cell, eight are employed, placed end to end, and the steel springs that prevent the collapse of the ends are placed inside the cells. A pen at the end of the index arm moves up and down on a drum revolved by clockwork, making a continuous record of the *actual pressure* at the station.

A very ingenious recording mercurial barometer is shown in Fig. 37. The cistern *C* and the metallic case *B* are supported through the frame of the instrument by the wall of the room. The barometer tube swings perfectly free inside the case, and is suspended from one end of a balance beam at *h*. On the other end of the beam is a heavy counterpoise not shown in the figure, and the light traveling weight *W*. The mercury in the barometer tube acts simply as a nearly frictionless piston to maintain the vacuum in the tube, and the pressure of the atmosphere over an area on the end of the tube equal to the area of the cross section of its bore is thus applied to the end of the beam at *h*. Any slight change in the pressure will cause a tilting of the beam, thereby closing an electric circuit at *b* through the magnet *M* or *M′*, and turning the screw *S* in the proper direction to move the weight *W* so as to reëstablish the equilibrium of the beam. An arm carrying a pen is attached to the carriage that moves *W*, and this records on a drum (not shown) that is revolved by the clock at *C′*.

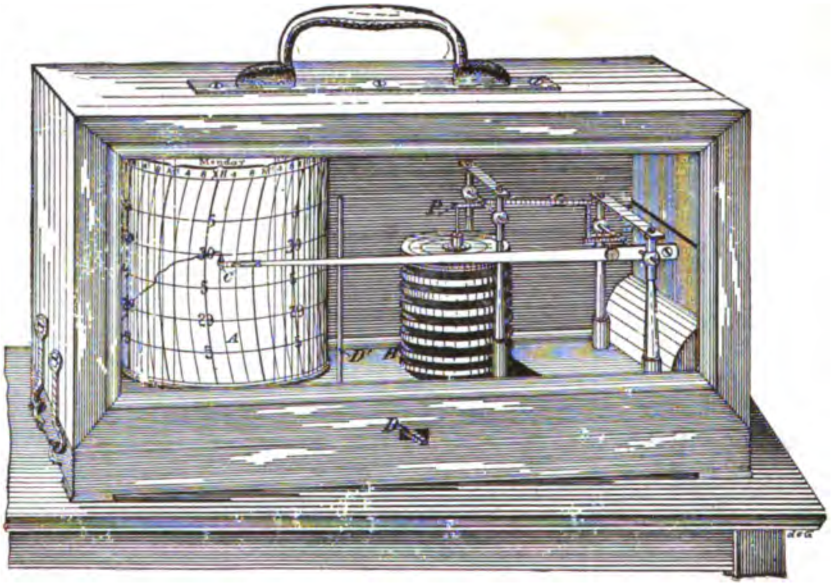

FIG. 36.—ANEROID BAROGRAPH.

The principal error in the indications of this barograph arises from the effect of capillary action between the mercury and the glass, this error

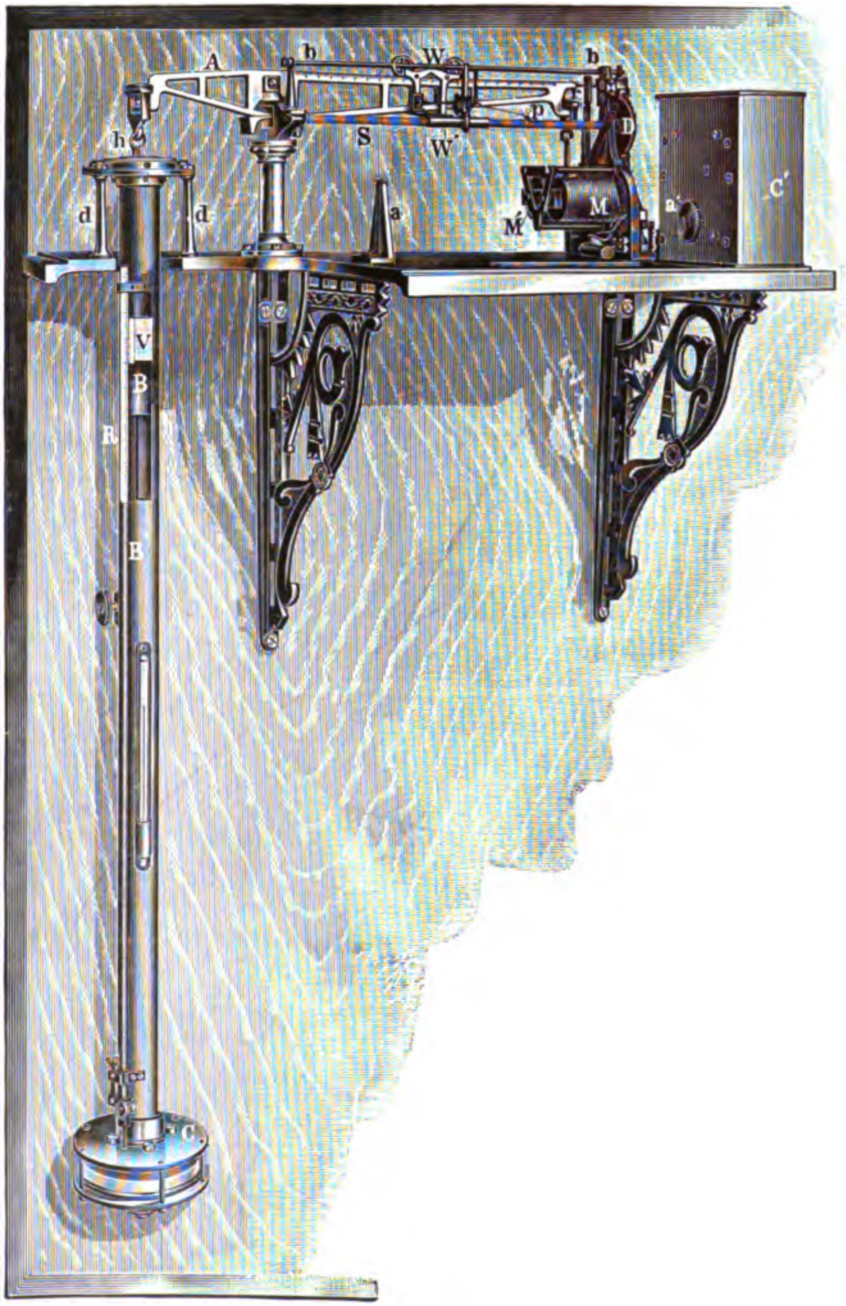

FIG. 37.—MARVIN NORMAL BAROMETER.

differing somewhat for rising and for falling pressure. A scale *R* and a vernier *V* are attached to the barometer tube, by means of which direct readings of the height of the barometer may be made. The instrument is therefore not only a barograph, but also a very accurate barometer of the fixed cistern type.

The Horizontal Distribution of Pressure.—Table XXIV shows the pressure distribution in latitude, the annual pressure after Ferrel, and the January and July pressures after Spitaler.

TABLE XXIV.

Variation in Atmospheric Pressure with Latitude.

LATITUDE.	January.	July.	Year.
N. 80°	757.5 mm.	758.8 mm.	760.5 mm.
75°	58.3 mm.	58.0 mm.	60.0 mm.
70°	60.1 mm.	57.6 mm.	58.6 mm.
65°	62.0 mm.	57.5 mm.	58.2 mm.
60°	60.8 mm.	57.7 mm.	58.7 mm.
55°	61.1 mm.	58.1 mm.	59.7 mm.
50°	62.3 mm.	58.9 mm.	60.7 mm.
45°	63.0 mm.	59.6 mm.	61.5 mm.
40°	63.9 mm.	60.0 mm.	62.0 mm.
35°	64.8 mm.	59.8 mm.	62.4 mm.
30°	65.0 mm.	59.3 mm.	61.7 mm.
25°	64.0 mm.	58.5 mm.	60.4 mm.
20°	62.3 mm.	58.0 mm.	59.2 mm.
15°	60.5 mm.	57.5 mm.	58.3 mm.
10°	59.1 mm.	57.7 mm.	57.9 mm.
5°	58.2 mm.	58.5 mm.	58.0 mm.
Equator	58.0 mm.	59.1 mm.	58.0 mm.
S. 5°	57.9 mm.	60.0 mm.	58.3 mm.
10°	57.8 mm.	60.9 mm.	59.1 mm.
15°	57.8 mm.	62.0 mm.	60.2 mm.
20°	58.5 mm.	63.5 mm.	61.7 mm.
25°	59.7 mm.	64.7 mm.	63.2 mm.
30°	61.0 mm.	65.1 mm.	63.5 mm.
35°	62.0 mm.	63.9 mm.	62.4 mm.
40°	61.9 mm.	60.6 mm.	60.5 mm.
45°	58.2 mm.	57.1 mm.	57.3 mm.
50°	752.7 mm.	752.8 mm.	53.2 mm.
55°	....	....	48.2 mm.
60°	....	....	43.4 mm.
65°	....	....	39.7 mm.
70°	....	....	738.0 mm.

Belts of maximum pressure at about latitude 35° north and south are clearly shown, and also a belt of low pressure at the equator, all of which move north and south appreciably with the annual march of the sun. An increase of pressure is indicated from latitude 60° or 65° north to the pole in July.

Isobars.—In order to represent graphically the distribution of pressure over the earth's surface it is customary to draw lines through points having the same sea-level pressure. These lines are called *isobars.* They are the lines in which the isobaric surfaces would cut the surface of the globe if it were everywhere reduced to the level of the sea.

Barometric Gradient.—By barometric gradient is meant the rate of change of pressure along a horizontal surface. The distance between isobars shows the steepness of the barometric gradient. The unit of horizontal distance usually employed is the length of 1° on a meridian. Thus, if the difference in pressure between two points is 1 inch, and the distance between them is equal to the length of 10° on a meridian, the barometric gradient is 0.1 of an inch.

We may compute the effective force of a barometric gradient as follows: The length of 1° on a meridian is about 69.5 miles, or 364,525 feet. The height of a column of air equal to 0.1 inch of pressure at sea level is about 95 feet; a gradient of 0.1 inch therefore corresponds to $\frac{95}{364525}$, or 0.00026 of gravity.

Seasonal Distribution of Pressure.—Charts 6 and 7 show the sea-level isobars for January and July respectively. On Chart 6, in the northern hemisphere, are two great areas of high pressure overlying the continents of Asia-Europe and North America, with great areas of low pressure overlying the north Atlantic and the north Pacific oceans. The belt of high pressure at latitude 30° is, however, everywhere discernible. In the southern hemisphere there are three high areas over the Pacific, Atlantic, and Indian oceans, respectively, at about latitude 30°, with slight depressions at about latitude 5° over the continents of South America, Africa, and Australia.

Chart 7 shows a very different pressure distribution. In the northern hemisphere there are areas of high pressure over the Atlantic and the Pacific oceans at about latitude 35°, with a decidedly low area over Asia, the minimum occurring at about latitude 25°, and a less marked low area over North America, with its minimum at about latitude 40°. In the southern hemisphere there is a marked belt of high pressure at about latitude 30°, with a tendency to form maxima over the oceans, as in January. On both these charts it is easy to trace the low-pressure belt near the equator, and the diminution in pressure from about latitude 30° toward the south pole is very marked as far as observations have been made. The pressure gradients in north polar regions are much less pronounced.

Charts 6 and 7 should be compared with Charts 4 and 5 of Chapter

VII, isanomalous lines for January and for July, respectively. The effect of the unequal heating of the atmosphere in latitude, referred to by Teisserenc de Bort,[1] is very apparent. At the same time the tendency to form the belts of high and low pressure called for by Ferrel's[2] theory is not obliterated.

Annual Variation in Pressure.—From what has been said it will be seen that there is a close relation between temperature and pressure. High temperature expands the volume of the air and causes an overflow at high levels and a decrease in the pressure at the surface. The result is that land areas have maximum pressures in winter and minimum pressures in summer, while the reverse is true of ocean areas. Regions of considerable elevation also have a maximum of pressure in summer, for the reason that when the air is cold and dense a greater percentage of its mass is below their level than is the case when the air is expanded by heat.

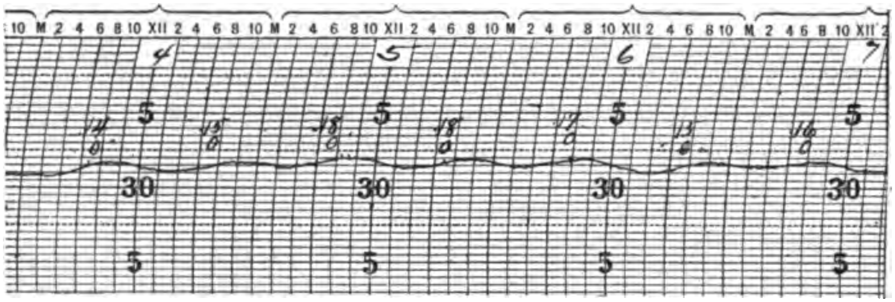

Fig. 38.—Barograph Trace for Key West, Florida, March 4–7, 1908.

Diurnal Change in Pressure.—Fig. 38 is a barograph trace for Key West, Florida, showing the diurnal changes in pressure. In temperate zones these diurnal fluctuations are nearly masked by nonperiodic fluctuations, but hourly means for long periods of time eliminate the nonperiodic fluctuations, and we are then able to detect the diurnal fluctuations. Dr. Fassig has investigated the character of these diurnal fluctuations,[3] and he likens them to anticyclonic and cyclonic areas, or waves of increasing or diminishing pressure, that approach the American continent from the Atlantic, cross it, and pass off into the Pacific.

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[1] Report on the present state of our knowledge respecting the general circulation of the atmosphere, presented to the Meteorological Congress at Chicago, August, 1893, by L. Teisserenc de Bort.

[2] "Recent Advances in Meteorology," *Report of the Chief Signal Officer*, 1885, Part II.

[3] "The Westward Movement of the Daily Barometric Wave," by Oliver L. Fassig, Ph.D., U. S. Weather Bureau, *Bulletin No. 31*, pp. 62–65.

Chart 8 shows the primary anticyclonic area, or wave of increasing pressure, at 9 A.M., 75th meridian time. The area or wave, of diminishing pressure, is approaching from the African coast. Chart 9 shows this primary cyclonic area at 3 P.M., the primary anticyclonic area having passed off into the Pacific, while a secondary anticyclonic area is approaching from Africa.

Chart 10 shows the position of the secondary anticyclonic area at 10 P.M., with the secondary cyclonic area approaching from the west, while Chart 11 shows the secondary cyclonic area at 4 A.M. with the primary anticyclonic area approaching. These charts are based on data for the month of July. It is seen that these diurnal fluctuations are greatest in the tropics, and are hardly noticeable in polar regions. They are undoubtedly connected with the diurnal temperature fluctuations.

Vertical Distribution of Pressure.—In the section on mercurial barometers it was stated that barometric readings are reduced to what they would read at sea level by adding to each the inches of mercury equivalent in weight to the column of air between the barometer cistern and sea level. The determination of the weight of this column of air, or, in other words, the correction to be applied to the reading of a barometer in order to reduce it to sea level, is not a simple matter. It depends in general upon the height of the observing station above sea level, the mean temperature of the air column between sea level and the altitude of the station, the amount of moisture in this air column, and the intensity of gravity, all of which vary with both latitude and altitude. A full discussion of this subject will be found in the *Report of the Chief of the Weather Bureau,* 1900–1901, vol. ii, Chapter II.

Humphreys computes the vertical pressure gradient to be as follows:

TABLE XXV.

Height.		Pressure.	
Kilometers.	Miles.	Millimeters.	Inches.
0	0	760	29.92
11	6	168	6.61
20	12.4	39.6	1.56
30	18.6	8.04	0.33
40	24.9	1.65	0.065
50	31.1	0.466	0.018
100	62.1	0.0076	0.0003
150	93.2	0.0043	0.00017

The cooler and drier the atmosphere the more rapid is the diminution of pressure with elevation. It, therefore, diminishes more rapidly in polar than in equatorial regions, and generally in anticyclonic than in cyclonic areas, as will be shown in the section on cyclones and anticyclones.

THE GENERAL CIRCULATION OF THE ATMOSPHERE

Halley's and Hadley's Efforts to Account for the Trade Winds.—Navigators early learned that in the tropics there were winds blowing almost continuously from the northeast in the northern hemisphere, and from the southeast in the southern hemisphere, with irregular winds from the west in extratropical regions. By some it was argued that the earth in rotating from west to east left the air in the tropics behind it. E. Halley,[1] an English astronomer, writing in 1686, pointed out that this explanation was inadequate, since it did not account for the calm belt under the equator, for the southwest winds off the coast of Guinea, or for the monsoon winds of the Indian Ocean. He undertook to show that the sun, by raising the temperature and expanding the air over the region upon which its rays fall nearly perpendicularly, would cause a continuous movement of the atmosphere in the direction of the apparent daily motion of the sun, or from the east toward the west.

George Hadley,[2] another English astronomer writing in 1735, showed that this could not be the case. On the contrary, the effect of the diurnal heating by the sun should be to cause the air to flow in from all sides toward the heated area, *and from the west as well as from the east.* But especially should there be a flow of air toward the tropics from the cooler regions in higher latitudes. Since, however, air moving from higher to lower latitudes passes successively over parallels having increasing easterly motion, it would, on account of its momentum, fall behind the diurnal motion of the earth, and be deflected more and more toward the west. Furthermore, over the warmest belt it would tend to rise. In rising it would cool by expansion, so that in flowing away from the equator, as it must do to make room for the air continually flowing in at the surface, its tendency would be to gradually fall, reaching the surface in temperate latitudes.

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[1] "An Historical Account of the Trade-Winds and Monsoons Observable in the Seas Between and Near the Tropicks; with an Attempt to Assign the Physical Cause of the Said Winds," by E. Halley, *Miscellanea Curiosa,* vol. i, p. 61, London, 1762.

[2] George Hadley. "Concerning the Cause of the General Trade-Winds." London, 1735. (Reprinted in G. Hellmann's "Neudrucke von Schriften und Karten über Meteorologie und Erdmagnetismus," No. 6. Berlin, 1896.)

Cause of Westerly Winds of Temperate Latitudes.—The air, in going from low to high latitudes, passes successively over parallels of latitude having less and less eastward motion, so that it runs ahead of the diurnal rotation of the earth in high latitudes, or is deflected more and more toward the east, finally giving us the prevailing westerly winds of temperate zones.

Winds Deflected by Earth's Rotation.—Hadley did not understand that the deflecting force due to the rotation of the earth acts at *right angles* to the direction of motion, and consequently neither accelerates nor retards the speed of the wind; likewise, he did not know that it deflects east winds and west winds as well as north winds and south winds, except immediately over the equator. His fundamental principles, the first, that wind movements are primarily due to unequal pressure distribution produced by the unequal heating of the earth's surface, and the second, that the direction is greatly modified by the rotation of the earth, were, however, correct, and his theory of the circulation was generally accepted, and suffered little modification in the century following its publication.

Upper Air Circulation Suggested by M. F. Maury.—Fig. 39, Diagram of the Winds, which is taken from Maury's "Physical Geography of the Sea," published in 1855, is a representation, with only slight modifications, of the circulation as outlined by Hadley. The arrows in the body of the figure inside the circle give an approximation, but not a close one, to what observation has shown to be the prevailing direction of the surface winds when the average is taken of a period sufficiently long to eliminate the irregularities due to cyclonic action; but the attempt to show, outside the circle, the upper air circulation is purely speculative and should not be seriously considered.

FERREL'S THEORY OF CIRCULATION.—William Ferrel[1] was so dissatisfied with Maury's theory that he investigated the subject from a higher mechanical viewpoint. First of all, in his mathematical solution of the problem he found it convenient to make certain assumptions relative to temperature distribution and the effect of friction, but eventually he dealt with actual conditions, so that his final results agree fairly well with observed facts. Ferrel assumed a frictionless earth, with a temperature gradient from the equator to the poles, but no temperature gradient along the parallels of latitude, and later showed that the unequal heating effects of continents and oceans produce marked gradients along considerable portions of the parallels, especially in the northern hemisphere.

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[1] See his early memoirs reprinted in *Professional Papers of the Signal Service*, No. VIII, 1882, and No. XII, 1882; "Recent Advances in Meteorology," by William Ferrel, *Report of the Chief Signal Officer*, 1885, Pt. II; and "A Popular Treatise on the Wind," New York, 1889.

The circulation resulting from Ferrel's approximate solution of the problem is shown in Fig. 40, in the body of which the broken arrows show the direction of the upper currents, and the full arrows the direction of the surface currents. This figure is reproduced more to show the historical development of the theory of atmospheric circulation than as an illustration of what actually occurs over the whole earth. The arrows inside the inner circumference fairly well represent the winds at the surface and at the level of the highest clouds, except that more recent observations show that the northerly component is less than here shown both at the surface and at upper levels over the middle and high latitudes. Many years' observations conclusively prove that for these latitudes the prevailing direction at the cirrus level (about 6 miles) is almost exactly toward the east, as in Fig. 40; the European observations show directions

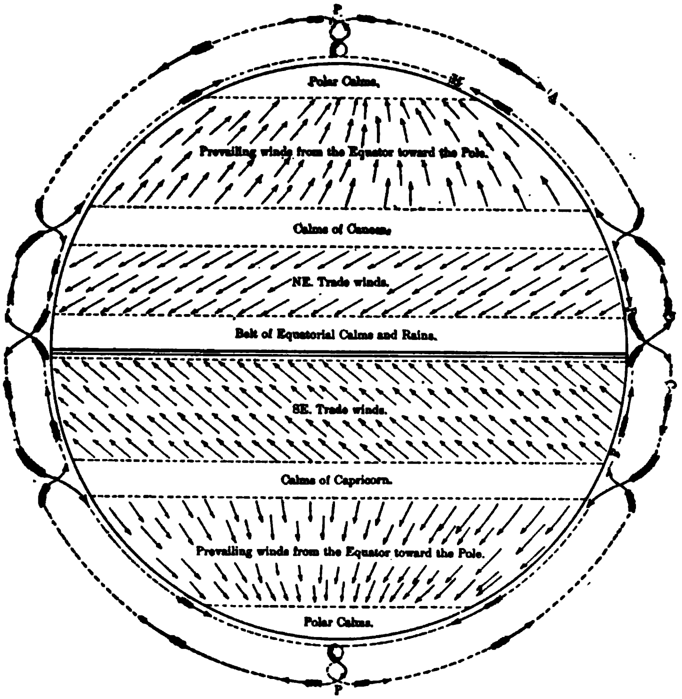
P
Polar Calms.
Prevailing winds from the Equator toward the Pole.
Calms of Cancer.
NE. Trade winds.
Belt of Equatorial Calms and Rains.
SE. Trade winds.
Calms of Capricorn.
Prevailing winds from the Equator toward the Pole.
Polar Calms.
P

FIG. 39.—MAURY'S THEORY OF PLANETARY CIRCULATION.

that vary from a few degrees north of east to a considerable departure south of east. Ferrel's complex manner of accounting for the exchange of air between the equator and the poles, as illustrated by the arrows outside the inner circle, in but small measure agrees with observations, which, however, are insufficient to permit of a satisfactory charting of the planetary circulation, except at the surface of the earth and up to only moderate elevations.

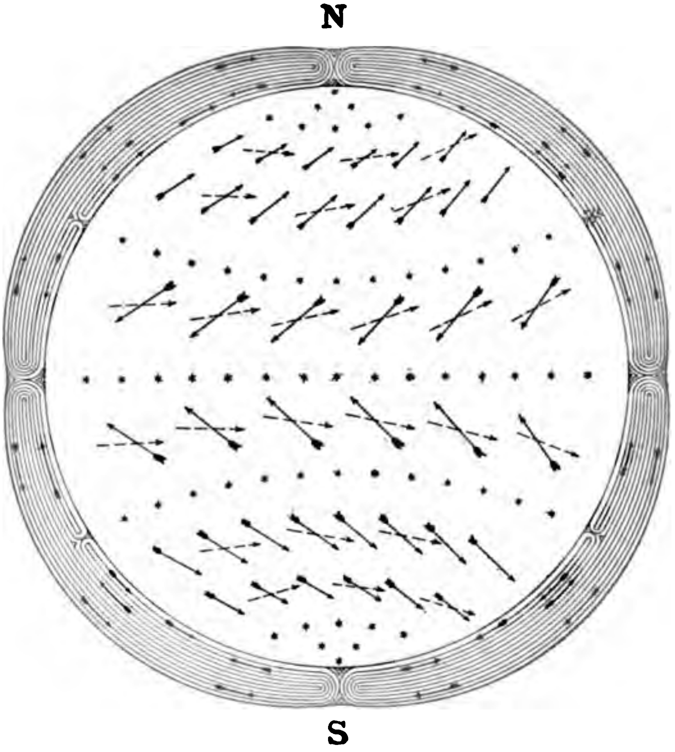

Fig. 40.—Coffin's Winds and Ferrel's Circulation.
(Broken arrows fly with highest clouds.)

Bigelow,[1] from his study of cloud movements, was unable to detect the poleward currents in the upper strata, and the equatorward currents in the lower strata, with a calm stratum between as called for by Ferrel's theory.

The Poles and the Equator Centers of Vast Cyclonic Whirls.—Partly as required by Ferrel's theory, we find that from the isothermal level downward to the surface, between latitudes 30° and the poles, there are cyclonic circulations, central at either pole. The centrifugal force of these winds, because they run ahead of the earth, is greater than it would be if they ran only with it, and consequently the air of high latitudes, as it encircles the globe, tends to pile up over latitudes farther south.

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[1] *Report of the Chief of the Weather Bureau*, 1898–99, vol. ii.

Within the tropics, however, the air flows toward the equator from either side and lags behind the earth, creating an anticyclonic whirl that exerts a slight pressure gradient toward the poles.

Cause of the High-pressure Ridges at Latitudes 30° North and South.—These two counter pressures—the pressure of the air of high latitudes toward the equator, and that of the equatorial air toward the poles—necessarily produce ridges of high pressure that encircle the earth nearly parallel to the equator. Besides, the intense heating of the tropics expands the air and causes it to overflow to the sides below the isothermal level, thus increasing the equatorial flow, and of course correspondingly increasing the high-pressure ridges at latitude 30°. The surface inflowing air from each side of the equator constitutes the trade-winds.

The resulting barometric pressure along a meridian is shown by the broken lines in Fig. 41. At high levels the maximum pressure occurs over the equator because heat elevates the isobaric surfaces, while at the surface the maximum occurs at latitude 30° (*e*, Fig. 41), which is on the saddle between the two hemispherical cyclonic whirls.

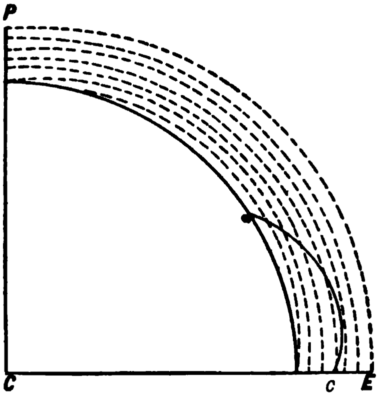

FIG. 41.—VERTICAL DISTRIBUTION OF PRESSURE ALONG A MERIDIAN. (Ferrel.)

Great Centers of Action.—At the International Meteorological Conference held at Chicago in 1893, L. Teisserenc de Bort called attention to the incompleteness of the theories of Ferrel and others, in that they ignored the temperature gradients along parallels of latitude, which in many cases are greater than the gradients along the meridians. Maps of winds, temperatures and pressures at sea level for nearly the whole globe were compiled by Buchan in 1868 and again in 1889, and by de Bort in 1893. Both authors pointed out the controlling influence exerted upon the circulation by areas of high and of low pressure of great magnitude, which the latter termed the *great centers of action*[1] of the atmosphere.

The Disintegration of the General Circulation.—If the earth were without motion, and its atmosphere of a uniform temperature, hydrostatic pressure would cause the air to settle down in such a way that at a given elevation, as 1,000 or 10,000 feet, it would everywhere have the same barometric pressure. But on account of temperature differences, and the rotation of the earth, the surfaces of equal pressure become much disturbed; and the lines in which they cut any given level, that of the sea, for instance, form loops and closed curves of various shapes and sizes. These isobaric lines may be compared to the topographical levels or contours that are drawn in an uneven country, and are useful in picturing to the mind the relative pressures in different places.

The seasonal modification, or complete interchange of location, of the principal highs and lows is due to the effect of land and water upon the temperatures of the air in the lower strata. The land warms more and cools more than does the water under the same condition of insolation, so that the oceans are cooler in summer and warmer in winter than the land masses on the same parallels of latitude. Areas of relatively high temperature correspond to areas of low pressure, and areas of relatively low temperature to high-pressure areas. Thus to the two causes of the general circulation—namely, the unequal heating of equatorial and polar regions and the deflection due to the earth's rotation—there is added a disturbance due to the thermal gradients between oceans and continents.

The flow between warm and cold masses of air dominates the circulation throughout the entire atmosphere. The principle may be illustrated by Fig. 42. Suppose that there is at any level a layer of air having uniform temperature distribution throughout, and suppose that a section of it is heated from any cause, so that it is warmer than adjacent sections, as is the case in the tropics. Then, as a result of this heating, the air will be expanded and its isobars raised above the level of the corresponding isobars of the adjacent colder sections, and therefore

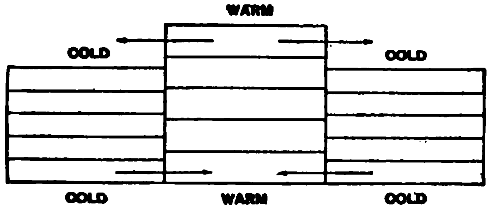

Fig. 42.—Flow Between Warm and Cold Masses of Air.

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[1] Closed areas of high or low pressure, which have a certain permanence in a given season, and give to the general circulation its leading features.—Teisserenc de Bort.

through the action of gravity a circulation will set in causing the heated air to overflow the colder, and the colder to underrun the heated till the common level of the isobars is again established; *and because this flow is on the surface of a rotating sphere vortex motions are produced.*

DIRECTION OF VORTICAL ROTATION OF STORMS DIFFERENT IN NORTHERN AND SOUTHERN HEMISPHERES.—The rotation of the earth produces a counter clockwise motion of the incoming winds of the cyclones of the northern hemisphere, and the opposite movement in those of the southern. Exactly the reverse of this obtains in the case of the outgoing winds of the anticyclones. The magnitude of this deflection is independent of direction and equal to the effect at the pole (where it is greatest), multiplied by the sine of the latitude of the place under consideration. The truth of this statement is easily seen by any one familiar with the composition and resolution of angular velocities.

LOCAL CIRCULATION

The Cause of Storms.—From the second preceding paragraph it is evident that the permanent hemispherical circulations are due to equatorial heating and polar cooling; that the Great Centers of Action, as illustrated by the Highs and the Lows on Charts 6 and 7, are mainly caused by the difference between the temperatures of oceans and continents; and, finally, that thermal irregularities on land or on water, in proportion to their intensities, will create such disturbances as cyclones, anticyclones, thunderstorms, tornadoes, and waterspouts.

Cyclones and anticyclones differ from the Great Centers of Action in many particulars—they are more violent, of smaller area, of short duration, and are migratory. In the middle latitudes they move rapidly from west to east and slowly toward the west or northwest in the tropics, following, as a rule, in both localities the border of a great high center of action. Likewise, thunderstorms, tornadoes, and waterspouts differ from cyclones in being smaller in area, more intense, and of shorter duration, and occurring within cyclones, near the outer border.

In the formation of these storms it does not matter in the least how the necessary difference between the temperatures of adjacent masses of air is established—whether by the local heating or cooling of a relatively quiet atmosphere, or by juxtaposition of currents in their circulation between hot and cold regions. In either case there will be, as explained, an over and an under running of the unequally heated masses along curved paths.

North America the Principal Breeding Ground for Storms.—Any theory to explain the origin of cyclones and anticyclones must account for the fact that Asia is singularly free from such disturbances. The great Himalayan range runs east and west near the southern part of this continent, and, naturally, interferes with the flow of currents of air from the Indian Ocean to the interior. On the other hand, in North America the Rocky Mountains run north and south along its western portions, and, while they tend to check the eastward flow of air in the lower strata, they permit the flow of warm currents from the south and cold currents from the north over the United States. Therefore, in Asia the mountains tend to prevent the conflict of currents that seem to be necessary to the formation of cyclones, while in North America they aid it. Hence it is that North America is the region of the most vigorous mixing processes in the northern hemisphere, and, in fact, in either hemisphere, and is the area upon which the most active cyclonic circulation takes place; for this reason it must be the special theater for meteorological studies upon the causes and effects of the thermodynamic and hydrodynamic forces operating in the lower strata of the atmosphere.

Construction of Weather Maps.—As an example of cyclones and anticyclones on the sea-level plane, the weather map for April 24, 1906 (Chart 12), and the map for March 6, 1908 (Chart 13), have been chosen. Lines of equal pressure, or isobars, are drawn through stations that have the same barometric pressure, the barometer as read at the station having first been reduced to the sea-level plane. Some of these isobars form closed curves, while others are mere sinuous loops. In the low area (cyclone) over Nova Scotia, the lowest pressure is 29 inches, and it is surrounded by a series of ovals increasing in size up to a pressure of 29.80 and 29.90 inches. Passing westward the high area (anticyclone) begins at 30 inches and the closed curves decrease in area to the maximum high pressure of 30.20 inches. In a similar way all cyclones and anticyclones are surrounded by closed curves. Sometimes these isobars assume nearly circular forms, of which the weather map for March 6, 1908, is taken as a typical example.

Special attention should be paid to the shape of the isobars to the northwest of the low pressure. Beginning near the center, with the isobar of 29.20 inches, the pressure gradually increases to 29.90 inches. In this region there are two isobars of the same pressure—29.90 inches—very near each other. To the northward as well as to the southward the pressure is lower, while to the eastward and westward the pressure is higher—namely, 30 inches and more. This region forms a *saddle*[1] of high pressure, and it is a characteristic feature in the configuration of the pressure lines of the maps. If, for example, the pressure at the saddle were generally lowered, the result would be that the 29.90 lines would coalesce to the east and west, while the 29.80 lines would approach nearer together. In this way there would be one less closed isobar surrounding the center. If, on the other hand, the pressure over this region gradually increases to 30, the lines would approach, coalesce, and break up into two curves, one closed, surrounding the center, and the other a mere loop, which would be a part of the group facing northward. As the air pressure rises and falls in different places, the closed isobars lock and unlock in the manner described on the given level. If we pass up through the atmosphere to higher level planes, as to 1,000 meters, or 3,000 meters, we shall find that the number of closed isobars gradually decreases, while the number of long looping isobars gradually increases. At a sufficiently high elevation all the closed curves will disappear so far as the cyclones and anticyclones are concerned, and there will be left only the great general isobars which surround the polar regions.

An example of the relation of the local isobars to the isobars of the general circulation is shown by Fig. 43.[2] The two subordinate whirls, marked 3 and 6, are the local cyclone and anticyclone, respectively. If at any center, as that marked 1, a series of circles be drawn tangent to the large circles and marked from −0.1 to −0.8, to show that some cause is operating to reduce the normal general isobars by the amount indicated, we can easily see the method by which the observed isobars were actually produced. For example, if the amount indicated on the small circles be subtracted from the pressure indicated at the point where they cross the large circles in succession, as −0.1 from 26.20, −0.2 from 26.30, −0.3 from 26.40, etc., we shall have a series of points whose value would be 26.10. Connect up all these points and we shall determine the new course of the 26.10 isobar; by making the proper detour in the other isobars effected we obtain the result given in 2, which almost exactly resembles the isobars shown on the map for March 6th. Of course, on the weather map there are always small irregularities that somewhat tend to obscure these geometrical conditions, but it is easy to follow the analogy. In 2 the dotted line, where it is marked 26.05, represents the saddle, the pressure being lower to the north and to the south and higher to the east and to the west.

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[1] Narrow ridge of pressure between two low-pressure areas.

[2] From Fig. 25, *Monthly Weather Review* of February, 1903.

Passing now to 4, there is a series of circles from + 0.1 up to + 0.8, superposed upon the general isobars surrounding the pole. Now make additions instead of subtractions, and proceed as in 2. For example, the line 26.80 in 4 shows how the whole series of isobars in 5 is formed. The dotted line, where it is marked 26.95, indicates the saddle, with the pressure increasing both north and south. Putting these two systems, 2 and 5, together, we have a configuration of the disturbed isobars 3 and 6, which corresponds closely with those observed on the weather map so far as contours are concerned.

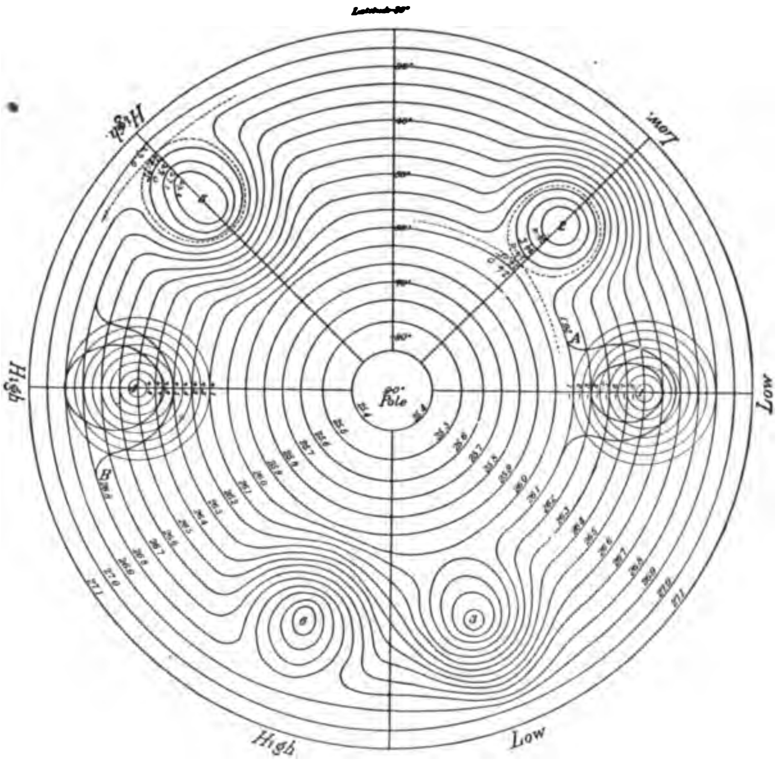

FIG. 43.—RELATION OF THE LOCAL ISOBARS TO THOSE OF THE GENERAL CIRCULATION. (Bigelow.)

Sometimes the small curves of cyclones and anticyclones are circular, as in our illustration; more often they are elliptical, and frequently they have no special geometric form.

High-level Isobars.—Tables have been constructed by which the barometric pressure can be reduced to different planes. By their use normal isobars for the United States have been constructed for each month of the year, on the sea-level plane, the 3,500-foot plane, and the 10,000-foot plane.

The appearance of these isobars on the upper levels, together with the circulation, is represented in Fig. 44. The circular isobars are shown on the sea-level plane; the closed isobars, saddle and loop are shown on the 3,500- and the 10,000-foot planes, while the undisturbed isobars are indicated in the cirrus cloud level, upon which floats the isothermal stratum. The closed isobars diminish upward and generally disappear at about the 10,000-foot level.

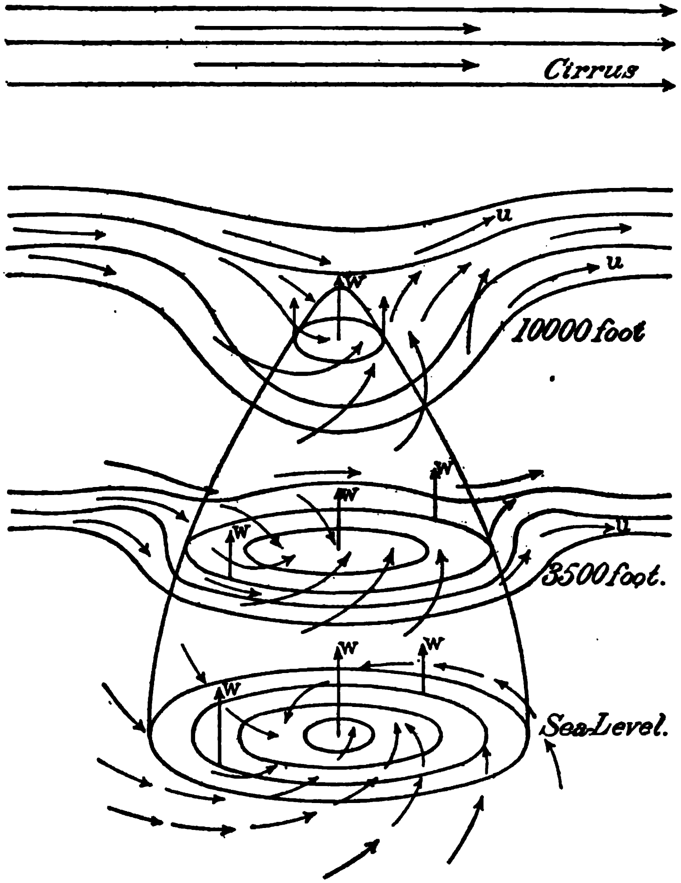

FIG. 44.—ISOBARS AND WINDS AT DIFFERENT LEVELS. (Bigelow.)

The Wind Vectors in Cyclones and Anticyclones.—It is convenient to have one word to indicate the general phrase "direction and velocity of the wind," and this word is vector. The *wind vector* generally indicates the direction toward which the wind is blowing and the speed with which it moves—as, for instance, 20 miles per hour toward the southeast. Ordinarily this would be described as a northwest wind of 20 miles per hour, as it is common to use the compass points with the direction reversed; but it is better to use a series of vectors drawn from a central point to the circle surrounding the center. The circle should be divided into degrees, with the 0° south, 90° east, 180° north, 270° west. This change in notation is indispensable in any mathematical discussion in which it is required to use the velocities in the equations of motion.

Movement of the Winds from the High- to the Low-pressure Areas.—Referring now to the weather maps of April 24, 1906, and March 6, 1908 (Charts 12 and 13), it will be seen that the winds in general blow out from the high areas by certain curves into the low areas. As a rule, the currents are stronger between the high and the low areas. On the east of the high, cold northwest winds mostly prevail; and on the east of the low they are mostly warm southeast. If these currents of the surface are carefully examined they seem at first sight to represent logarithmic spirals; that is to say, lines that make the same angle with the successive isobars as they approach the center of the low area, and recede from the center of the high area; but the currents really form stream lines of many curvatures which cannot be classified as simple logarithmic spirals.

When we pass from the surface of the ground to higher levels, as, for instance, to the region where the lower clouds are formed, including the cumulus and strato-cumulus, or to the region where the upper clouds prevail, including the cirrus, cirro-stratus, and cirro-cumulus, these wind vectors form different configurations,[1] as illustrated by Chart 14 for west Gulf highs, Chart 15 for west Gulf lows, and Chart 16 for tropical hurricanes. The direction of the wind at the surface is indicated by black lines; that of the lower clouds by blue lines; and that of the upper clouds by red lines. In the west Gulf high the vectors in the north and northeast quadrants flow quite nearly in the same direction at all levels, but in the southeast to the southwest quadrants the lower vectors generally have directions nearly at right angles to the upper and, in some cases, even move from opposite directions. In the west Gulf low the vectors of the three levels blow nearly together in the northwest and west quadrants, but in the southeast and east quadrants they are at right angles, or, in some cases, from opposite directions. This shows that while the currents in the cirrus levels flow eastward with only small disturbance in direction, those in the lower levels run in different directions. Generally speaking, warm currents from the south and cold from the north underrun the eastward drift at right angles, the coming together of these counter currents in moderate levels probably setting up local cyclonic and anticyclonic circulations, whose lowest section is shown on the synchronous weather maps.

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[1] This subject was studied by Bigelow in the years 1896–97, and an account of these vectors on different levels may be found in the "International Cloud Report for the Weather Bureau" in considerable detail. Charts 20 to 35 as well as several preceding charts, 13 to 19, of that report treat of these complex circulations.

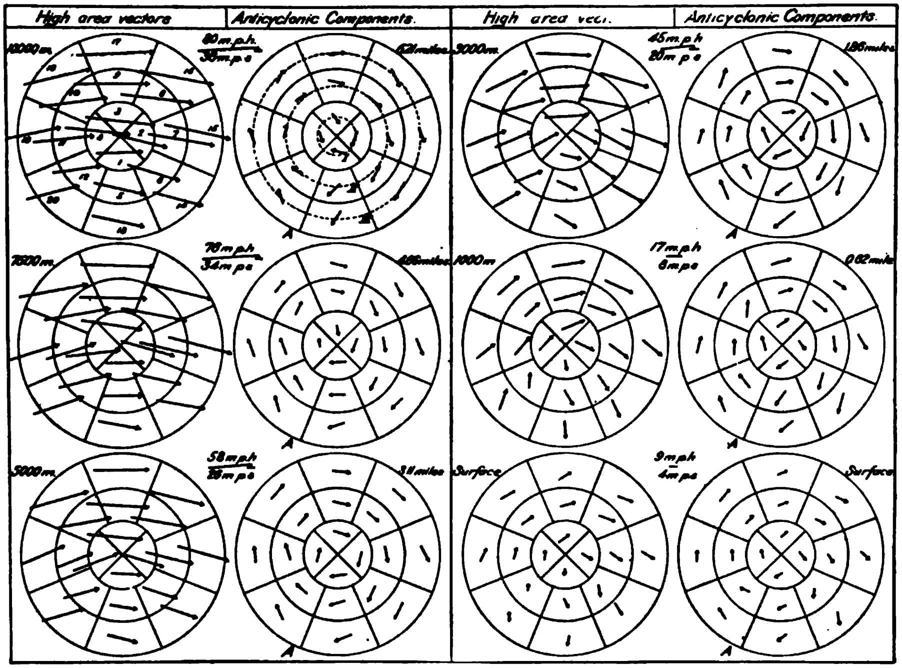


FIG. 45.—VARIATIONS WITH ALTITUDE OF ANTICYCLONIC VECTORS AND COMPONENTS. (Bigelow.)

In the case of the tropical hurricane (Chart 16), the center being located in the east Gulf states, it will be seen that the gyratory circulation of the lower levels has penetrated to great heights in all quadrants of the storm, inasmuch as the red arrows are closely associated with the blue and the black, being strongly deflected in the immediate neighborhood of the center of the low area. This is due to the fact that hurricanes are lofty circulations, spreading out not very broadly on the surface, while most cyclones are, in comparison, shallow circulations having wide bases. Thus the hurricane may be 6 miles or more high and 500 miles across, while a cyclone may be only 3 or 4 miles deep and 1,500 miles wide, as on the map of March 6, 1908. In other words, the hurricane is a violent cyclone.

Figs. 45 and 46 illustrate more fully the nature of the upper circulation. They refer to the following levels: Surface; 1,000 meters, or 0.62 mile; 3,000 meters, or 1.86 miles; 5,000 meters, or 3.11 miles; 7,500 meters, or 4.66 miles; 10,000 meters, or 6.22 miles. The areas surrounding the high and the low centers have been divided into 20 subareas for convenience, as marked on these diagrams, and the average wind vectors determined for all the clouds on different levels in each subarea.

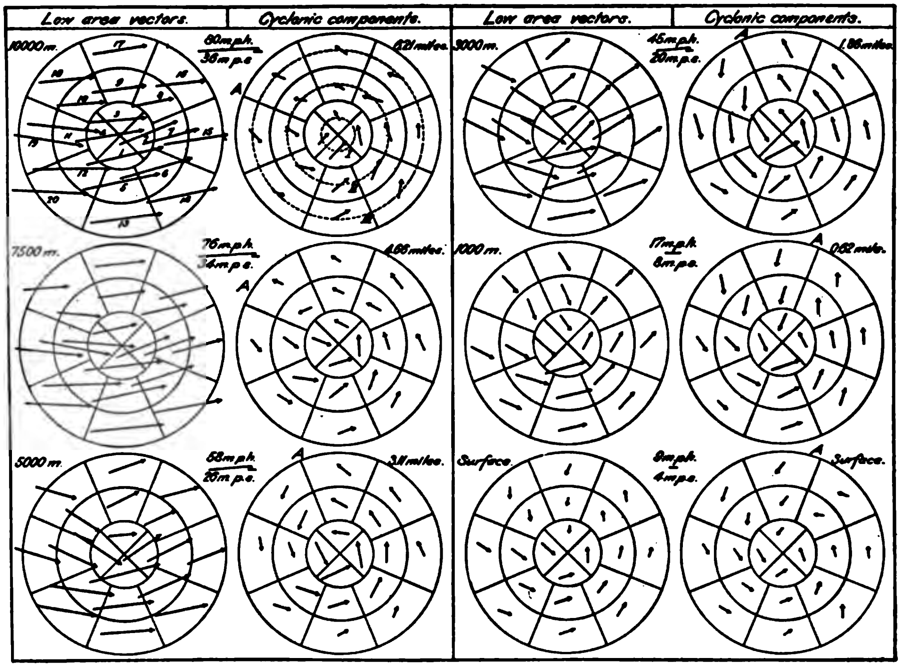


Fig. 46.—Variation with Altitude of Cyclonic Vectors and Components. (Bigelow.)

In addition, the average vectors of the general circulation, independent of local disturbances, have been computed for the same levels. They have a speed of 4, 8, 20, 26, 34, and 36 meters per second, or 9, 17, 45, 58, 76, and 80 miles per hour, respectively, and are directed a little north of east, as is shown diagrammatically between the figures giving the velocity in miles per hour and those giving it in meters per second. The observed vector in any area, and for any level, differs from the average vector for the same level by the addition of a small vector component, the magnitude and direction of which may easily be determined by the composition of vectors. By this means the cyclonic and anticyclonic vectors pertaining to the local circulation have been computed for each level, and they also are shown on Figs. 45 and 46.

Referring now to Fig. 45, it is seen that in anticyclones the speed of the wind increases with increase of elevation, and that at the same time its direction becomes more uniformly eastward until in the highest levels it follows a curve only slightly sinuous, with a convex side toward the *north.* Fig. 46 shows that in cyclones, also, the speed of the wind increases with increase of elevation and becomes more uniformly eastward, until in the highest levels it, too, follows a curve only slightly sinuous, but with the convex side toward the *south.* In the anticyclones the vectors in the northern subareas are longer than those in the southern, but in the cyclones they are longer in the southern subareas than in the northern.

The anticyclonic components at the surface are substantially the same as at other levels, though they are the longest on the 3,000-meter level, diminishing in strength upward and downward. They seem to be composed of two streams that flow the one past the other in the southern quadrant, that on the west side being pointed northward, and that on the east side being pointed southward, although this distinction is not pronounced. In the cyclone the components at the surface are likewise seen to have the same configuration as those in the upper levels, and they are also longest on the 3,000-meter level, diminishing in strength upward and downward. There seem also to be two currents, one northward and one southward, each flowing the one past the other in the northern quadrant. On the 10,000-meter level the line between the counterflowing currents is in the northwestern, and at successively lower levels it swings around into the northeastern quadrant. On the west side of this line of counterflow the currents flow southeastward or southward, and on the east side they flow northwestward or northward.

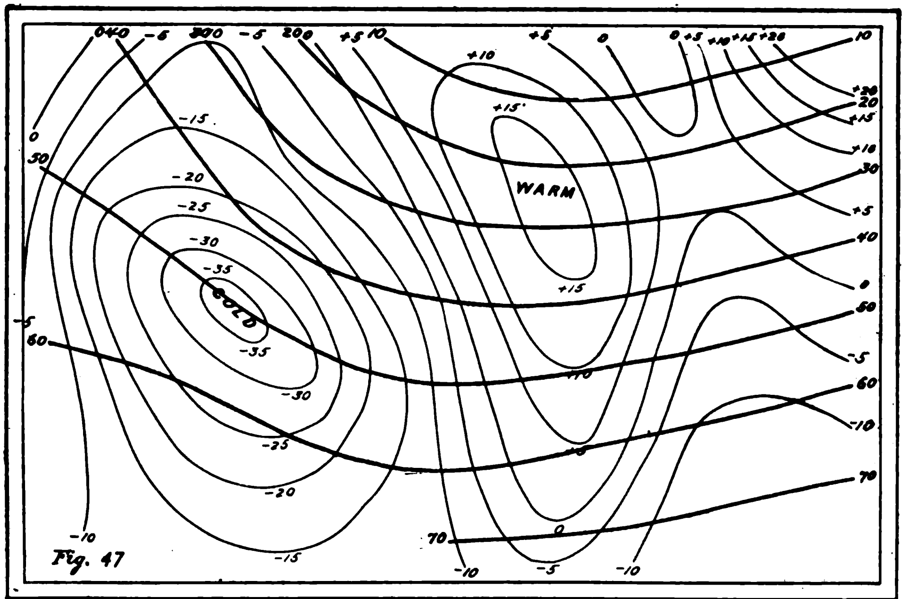
Putting the cyclonic and the anticyclonic systems side by side in succession, so that they shall be disposed in the order, high area, low area, high area, as is their usual arrangement on the weather map, it is perceived that a current is directed from the northwest to the west side of the low area, and from the south to the east side, with a tendency for each of these currents to curl the one about the other as they move spirally upward.

It will be next in order to study the distribution of temperatures in cyclones and anticyclones.

The Distribution of the Temperatures in Cyclones and Anticyclones.—Special attention should be paid to the distribution of the temperatures in the neighborhood of the high- and the low-pressure areas, as the theory of the causes and the effects involved in the local circulation is largely dependent on it. On the weather map for April 24, 1906 (Chart 12), looking from the east, it will be seen that the isotherms bend up and down among the isobars in a peculiar manner, the isotherms generally extending northward on the west side of the high and on the east side of the low, while they bend southward on the west side of the low and on the east side of the high. This can also be seen quite clearly on the same weather map where the isotherms are curved northward in the eastern quadrants of the cyclone and southward in the western quadrants.

The special point is made that *the cyclone as a whole is not a warm area nor is the anticyclone a cold area,* but that the increase of temperature is on the western side of the high area and on the eastern side of the low area, and that the decrease of temperature is on the western side of the low area, and on the eastern side of the high area. This is even more clearly seen on Figs. 47 and 48, which represent the weather map for February 27, 1903. Fig. 48 shows the relation of the isobars and isotherms. The normal typical isotherms for the United States have been determined for each month of the year, and those for February are shown on Fig. 47, being the long, nearly horizontal lines. If these normals be subtracted from the observed isothermal lines on Fig. 48 from point to point, and then the points of equal departure of temperature connected up, there will result the second system of lines on Fig. 47. This shows the distribution of the excess of temperature between the low and the high areas to the east, and the deficiency of temperature to the west of the low area.

TEMPERATURE DISTRIBUTION NOT SYMMETRICAL IN HIGHS AND IN LOWS.—This exhibit proves that the distribution of temperature is not symmetrical about the low and the high areas, as has been assumed in most theoretical discussions as to the mechanics of cyclones and anticyclones. On the other hand, the distribution is distinctly asymmetric, so that the centers of low pressure are nearly on the borders between the areas of warm and cold air. On Fig. 49 is given a diagram of the surface distribution of temperature in the equivalent circular cyclone. It was constructed from nine typical large cyclones whose centers were near the middle of Ohio, and the composite was made by compiling the data from point to point. It will be seen that the line of zero-departure, beginning at its northern extremity, passes southward a little west of the center and then



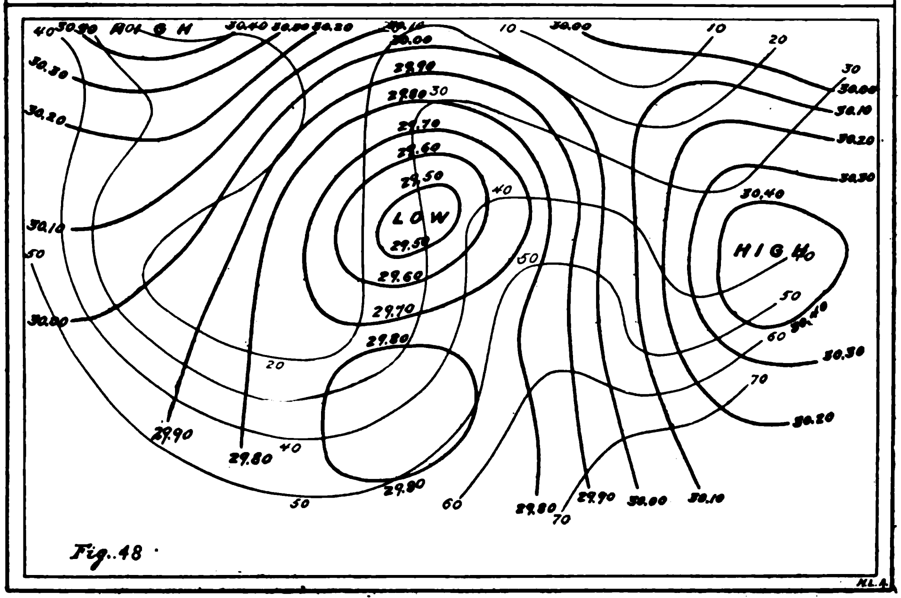


Fig. 47. Temperature Components for February 27, 1903.

Fig. 48. Isobars and Isotherms on the Weather Map for February 27, 1903.

southeastward, terminating east of the point of starting. The deficiency of temperature increases to a maximum in the southwest, while excess of

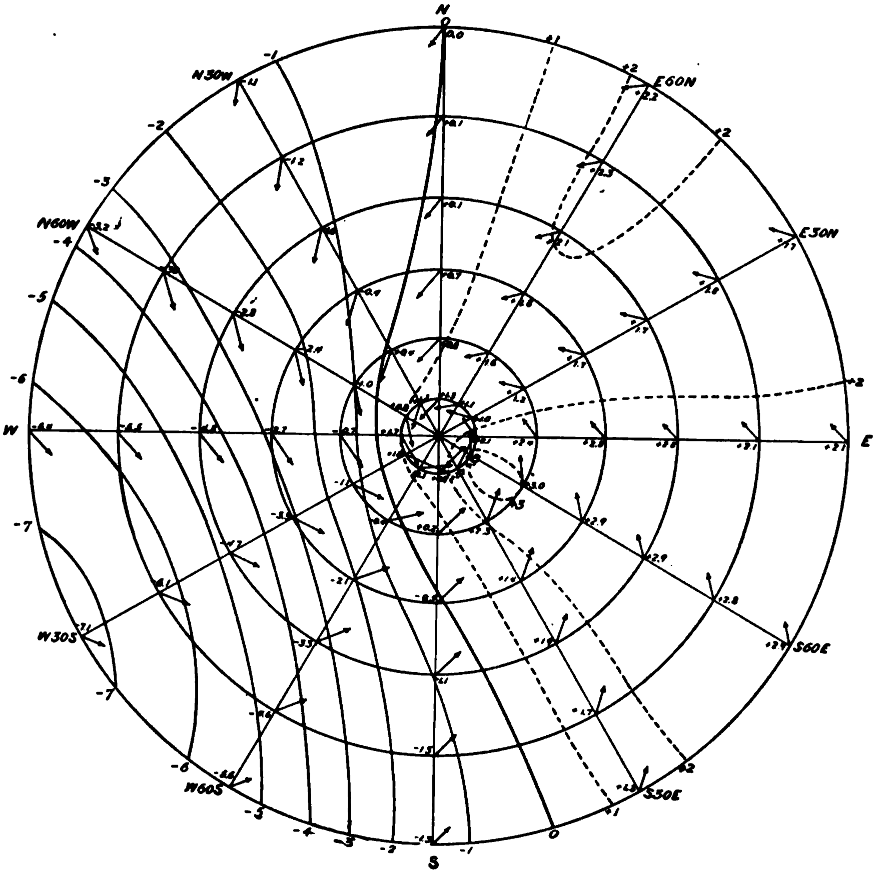


FIG. 49.—SURFACE DISTRIBUTION OF TEMPERATURE IN THE EQUIVALENT CIRCULAR CYCLONE. (Bigelow.)

temperature is general throughout the eastern areas, and there is a small maximum in or near the center.

TEMPERATURE DISTRIBUTION AT HIGH LEVELS IN HIGHS AND IN LOWS. —It is important to inquire whether this distribution of temperature persists above the surface of the ground. The results of a discussion of the Blue Hill observations made with kites (Fig. 50) show that in this country practically the same variations of temperature are found up to 4,000 meters. Fig. 51 shows that similar conditions prevail in Europe up to 6,000 meters, as derived from the balloon and kite observations made at

Hald and at Berlin. It will be noted that the warm south current, between the high and the low areas, tends to split into two branches to the northward, while the north current to the west of the low area tends to split into two branches directed southward.

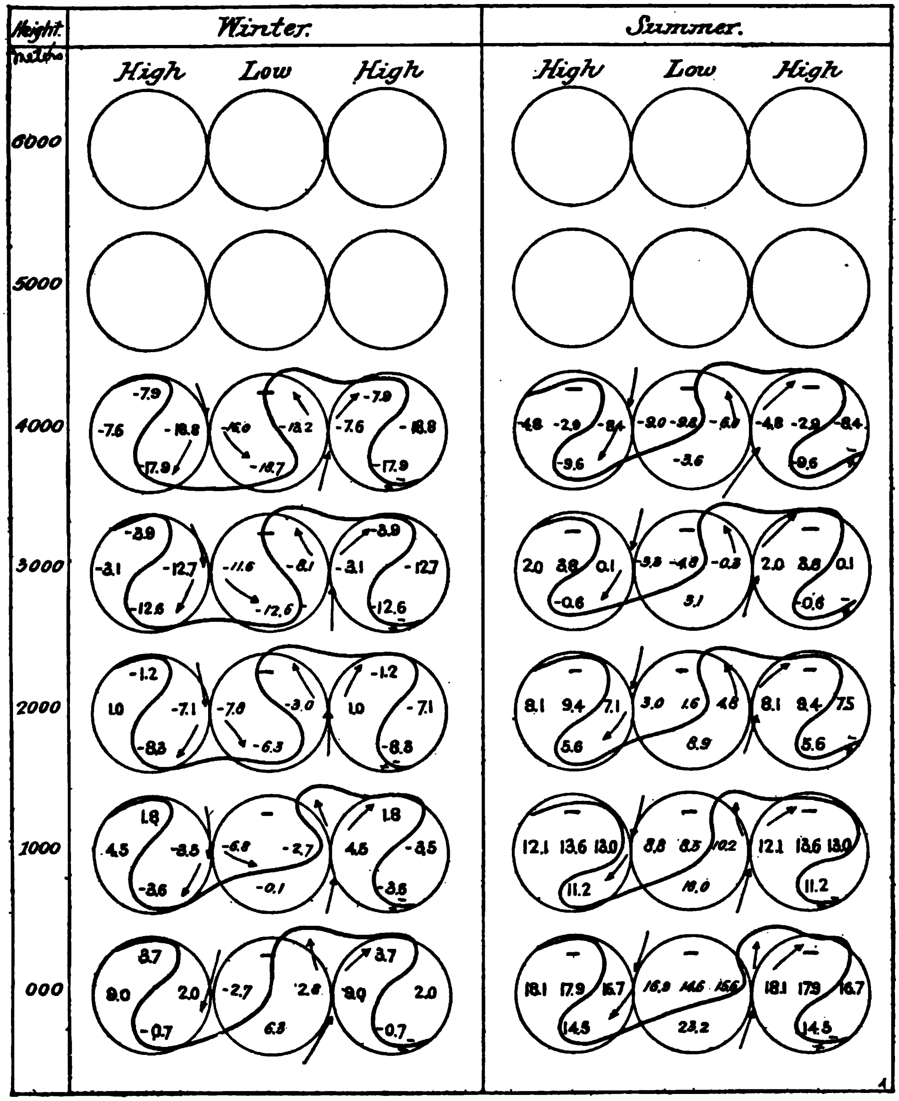


FIG. 50.—VERTICAL DISTRIBUTION OF TEMPERATURE IN AMERICAN CYCLONES AND ANTICYCLONES. (Bigelow.) (Figures in circles, centigrade temperatures.)

Summary of the Distribution of the Wind Velocities, Temperatures, and Pressures in Cyclones and Anticyclones.—It will now be desirable to bring together into one diagram the results that have been outlined. On Fig. 52 is given a diagram for each 2,000 meters from the surface to 10,000

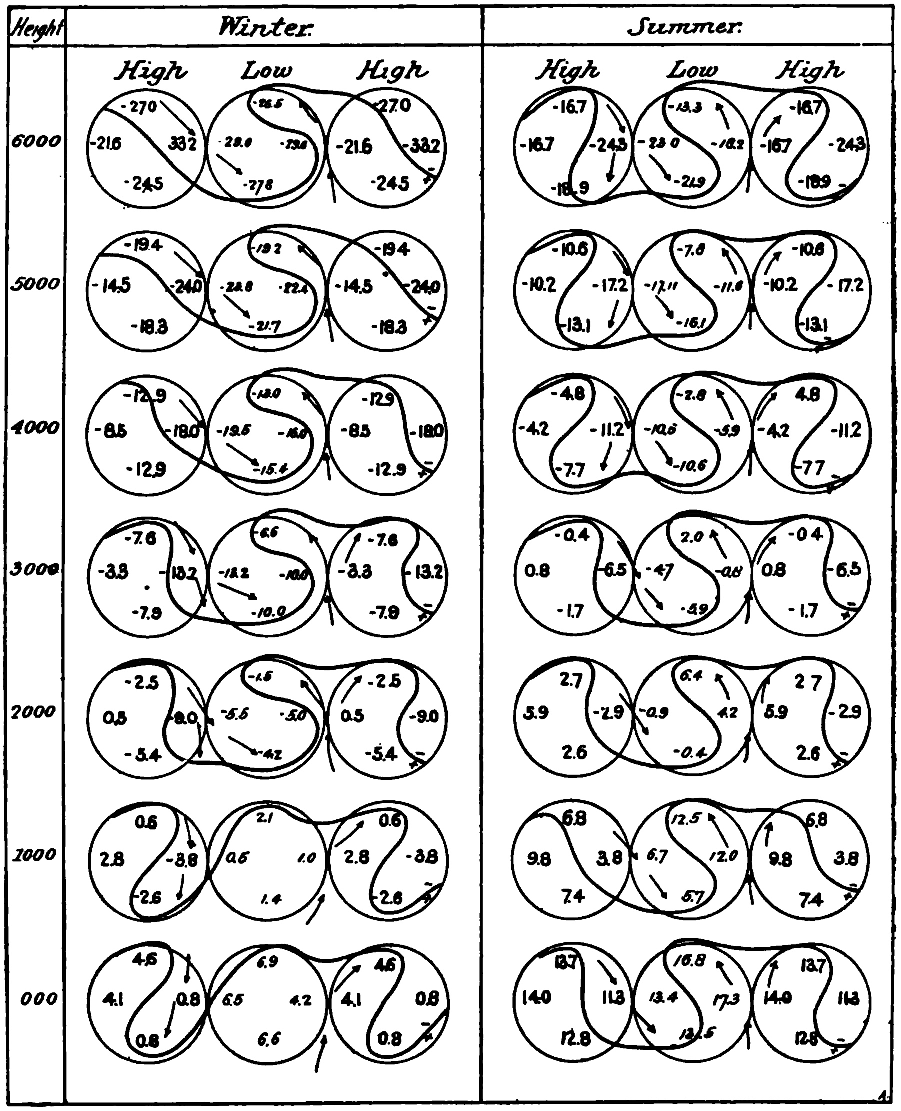


FIG. 51.—VERTICAL DISTRIBUTION OF TEMPERATURE IN EUROPEAN CYCLONES AND ANTICYCLONES. (Bigelow.) (Figures in circles, centigrade temperatures.)

meters high, showing the effect of cyclonic action on the temperature, the pressure, and the wind velocities. It is seen that the observed directions become more and more sinuous in descending from the 10,000-meter level, and gradually assume the characteristics on the sea-level plane. The inflowing current from the south splits up into two branches; the northerly currents also split up into two branches. The isotherms are depressed in latitude to the west of the low area, and they are elevated to the east of the low area. The maximum depression and the maximum elevation occur near the borders between the high and the low areas. The isobars at sea level show the saddle over the low area opening northward, and over the high area opening southward. In the higher levels the closed curves open up into loops, and they finally disappear in the 8,000- and 10,000-meter levels. In many cyclones the closed areas, especially in winter, persist up to the 4,000-meter level.

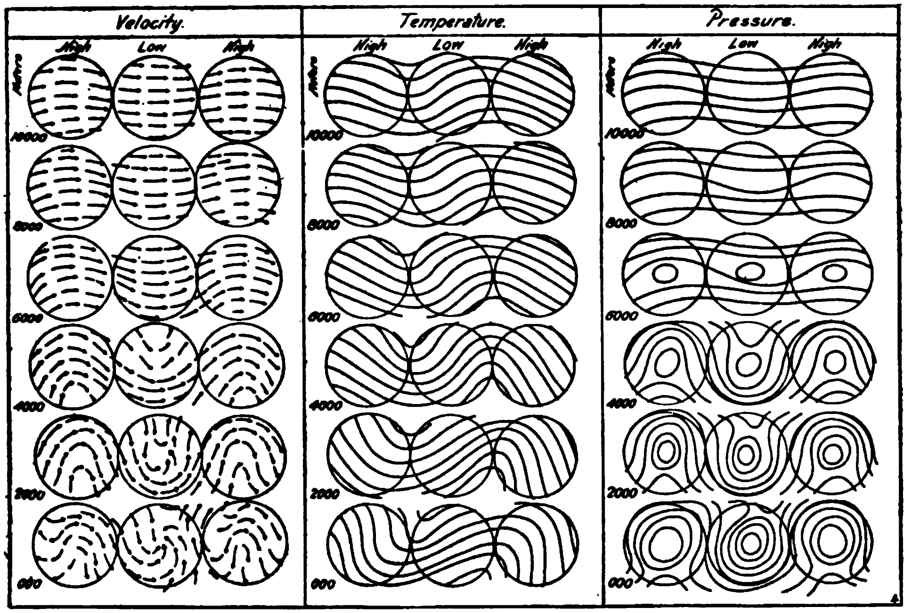


Fig. 52.—Vertical Distribution of Velocities, Temperatures, and Pressures in Cyclones and Anticyclones.

On Fig. 53 are given separately the components of the velocity, the temperature, and the pressure in all levels after the components of the general circulation have been eliminated. In the velocity the vectors are quite similar in all levels—that is, as far upward as the cyclonic disturbance is effective. It will be noted that there is a tendency for the saddle of the low area to rotate from the northeastern quadrant at the surface into the northwestern quadrant at the 10,000-meter level; beginning in the highest level and coming down to the lowest there is also a slight rotation of the saddle in the high area from southeast toward the southwest.

The area of excess of temperature lies on the east side of the low near the boundary between the high and the low pressures in all levels; the longer axis of this area tends to swing from a northeast-southwest direction into a northwest-southeast direction, on passing from the surface to the higher levels. Similarly, the area of the greatest cold is located near the boundary between the high and the low pressures, but on the west side of the low; and its axis also rotates in the same direction through about one quadrant. The direction of the component isobars undergoes a similar rotation in the low pressure, and there is a decrease in the intensity and number of the closed isobars in both the high and the low pressures.

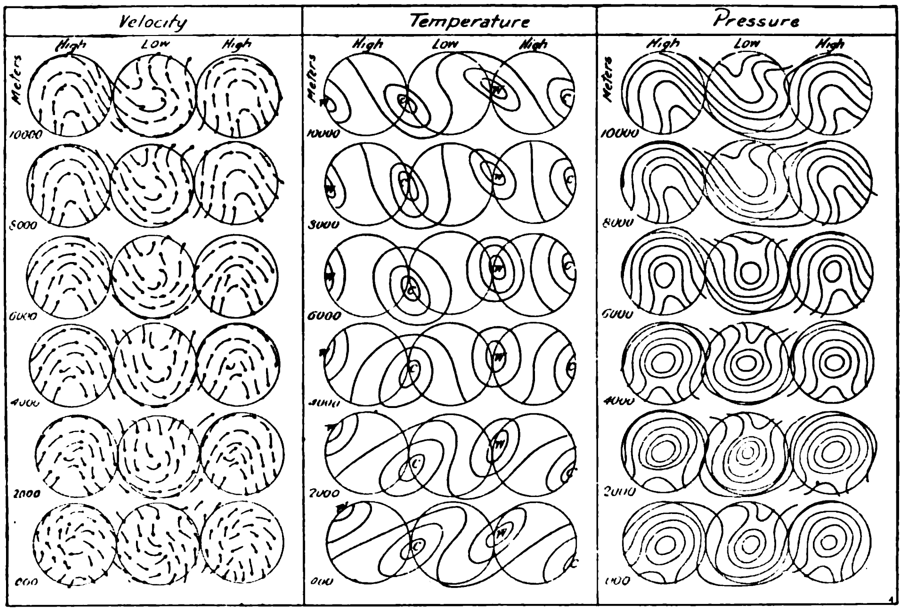


FIG. 53.—COMPONENTS OF VELOCITY, TEMPERATURE, AND PRESSURE AFTER THOSE OF GENERAL CIRCULATION HAVE BEEN ELIMINATED. (Bigelow.)

It should be understood that it is not possible to determine the curves in the upper levels with the degree of precision that is possible near the surface of the ground. Inasmuch as the cloud motions are our principal reliance in determining the movements of the air in the upper strata, it is unfortunate that clouds in the lower strata, which usually accompany cyclones, often cut off the view of the movements of the clouds in the upper levels. The temperatures up to 7,000 meters can be obtained by kites, but above that level free balloons must be employed.

Theories to Account for the Initiation and Maintenance of Cyclones and Anticyclones.—After considering the theories of Espy, Redfield, Ferrel, Dove, Bigelow, and the German school of meteorology, the author is of the opinion that cyclonic action can best be accounted for by the following assumptions and statements of observed facts:

Horizontal temperature gradients thousands of miles in extent produce comparatively shallow atmospheric streams which flow from the poles and from the tropics at only moderate elevations and are sustained for an indefinite time, but they may be deflected and their velocities added to or diminished by the unequal heating effects of land and water. These flow together, and because of the deflecting effect of the rotation of the earth cyclonic actions of vast extent and moderate intensity are initiated and maintained in the form of Great Centers of Action; and the circulation between these fundamental Highs and Lows in turn brings warm and cold currents into such relation that the migrating cyclones and anticyclones are formed, and these vortices seek to lift their heads into the region where the powerful eastward drift prevails, their upward and their downward discharges retarding this drift in the higher strata and accelerating the eastward motion of the lower air.

ASCENDING OR DESCENDING CURRENTS INSIDE ALL CLOSED ISOBARS.—Observations of the clouds prove that the cyclone is a form of circulation through which fresh portions of the atmosphere continue to stream. A careful examination of wind velocities shows that they increase steadily from the outer boundary of the cyclone toward the interior, and while it is not possible to actually observe the vertical components, yet it is probable that vertical motion sets in as soon as the first closed isobar is passed, almost imperceptibly at first, but increasing as each successive isobar is reached, until near the center the vertical component becomes large in comparison with the radial or tangential velocities. It may be laid down as a principle that where closed isobars exist there is an ascending or a descending current, according to the direction of rotation. Where the isobars wander about without closing up, it may be assumed that there is no rising or descending air.

LATENT HEAT NOT NECESSARY TO THE MAINTENANCE OF STORMS.—It is assumed by many that the maintenance of the vertical central current inside the closed isobars of the cyclone is due to the latent heat liberated by the condensation of aqueous vapor, but there are many objections to accepting this theory. To be sure, there are no visible sources of local heating in cyclones beyond the latent heat of precipitation, and in storms from the southern districts of the United States the rainfall is often of large amount, and in these the latent heat must add to the buoyancy of the center of the cyclone. On the other hand, there are many fully developed storms that form near the north Pacific coast and advance to the Gulf of St. Lawrence without precipitation worth mentioning. These prove that rainfall is not necessary for the formation or maintenance of cyclones, although it must add to their energy.

Ferrel supposed the temperature to be arranged *systematically about the center.* But a brief study of the isotherms in cyclones shows that this is not the case, since they usually trend from southwest to northeast, athwart the cyclone instead of being circular about the center, the resulting pressure gradient being such that the cyclone cannot be fed by an equal supply of air flowing in from each point of the compass.

The Ocean Cyclone.—The ocean cyclone may be distinguished from the land cyclone by its greater intensity. The land cyclone is described as a circulation that in some respects has features pertaining to a vortex of the dumb-bell type, but it is so imperfect that it cannot be classified under any of the simple types of vortex motion. The ocean cyclone, on the contrary, because of its greater velocity of rotation, especially in the central portions, more nearly resembles a true vortex. The clearest characteristic of such a vortex is this: That if any horizontal section be drawn through the vortex, the isobars on this plane shall be spaced in a geometrical ratio. That is to say, if the isobar of 30 inches is at a certain distance, as 775 miles from the center, the distance to the next inner isobar will be found on dividing its distance from the center by a certain factor, 1.5; the next one is found by a second division, and so on to the isobar nearest the center. Now the isobars of the land cyclone cannot be found by successive division with the factor 1.5, since the spacing is nearly uniform throughout the section, and this fact eliminates the land cyclone from the true vortex system.

There is another feature regarding these dumb-bell vortices to be noted. The dumb-bell vortex is shaped something like an hour-glass. Below the constricted part of the vortex the wind blows spirally inward and upward; above, spirally upward and outward. On the lowest plane the wind is directed along the radius toward the center and there is no tangential velocity; on the uppermost plane it is directed away from the center along the radius, and there is also no tangential velocity; in the pure vortex, on each pair of intermediate planes equally distant above and below the central plane, the wind makes the same angle with the radius, increasing from zero degrees at the top and the bottom planes to 90° at the center. If a horizontal section be drawn through the dumb-bell vortices at any level, the wind will make the same angle with the radius at every point on the plane, whether near the central axis or away from it. Now in nature the sea level forms such a truncating plane and cuts off these dumb-bell vortices at a certain section where the average inflowing angle is presumably 30° or 40°.

In the land cyclone the central plane is 3,000 to 4,000 meters high. The wind, instead of flowing outward with an increased angle above this plane, has been shown to continue to flow inward, or else to alternate between inflowing and outflowing currents. The inflowing angle is doubtless what it is in conformity to the section of the incomplete or truncated vortex. Where the observations are made, as at the sea level, the upper plane and the lower plane are not observed, the lower plane being below the sea level and the upper plane distorted by the rapid eastward circulation. A pure vortex of course requires for its development motion in a perfect gas or medium, where the internal friction can properly be neglected, but this is not the case in atmospheric vortices, because of the struggle with the eastward drift, which disturbs the formation of the vortex penetrating into the higher levels to such an extent that the vortex cannot be said to be perfect in any of these primary features.[1]

The Hurricane.—A more perfect system of vortices in the atmosphere is observed in the hurricane or typhoon, the tornado and the waterspout. These are quite perfect vortices of the dumb-bell-shape type, which has been described in connection with the ocean cyclone. They differ the one from the other merely in their dimensions, and the same mathematical principles apply to each of them.

The principal characteristics of the hurricane may be summarized as follows: In the cirrus cloud level, 10,000 to 12,000 meters above the sea, the clouds are observed to move in radial directions outward from the center in all directions. The outward-moving clouds represent the radial velocities in the upper levels of the dumb-bell vortex, while the inner wind velocities found on the sea level occur on the plane which truncates the vortex at some distance above the theoretical lower boundary plane, which is about 3,000 meters below the sea level. The middle plane, where the vortex curves approach the central axis most nearly, is about 3,000 meters above sea level. The inflowing angle of the wind on the sea-level plane corresponds to the section which is about one third the distance from the middle plane toward the boundary plane hidden beneath the level of the ocean. In a selected typhoon, the vertical distance from the sea level to the upper boundary plane is about 12,000 meters, and the horizontal distance from the center to the extreme radial velocities in the cirrus levels is probably about 700,000 meters. The vortex lines, which are represented by the isobars on the sea level, are spaced by a geometrical law already described, and approach nearer and nearer to each other in the neighborhood of the axis. These curving lines cut off a series of vortex tubes,[1] in each of which the air is rising and rotating around the axis. The same amount of air is rising through each section of these vortex tubes, and the radial, tangential, and vertical velocities are so adjusted by the vortex law as to make this possible. Of course, in fact the air rises in a series of spirals directed inward in the lower levels and outward above the middle plane. The radial velocity diminishes up to the middle plane and then increases outward; the tangential velocity increases up to the middle plane and then diminishes above it, and the vertical velocity increases up to the middle plane and then gradually diminishes. Near the center the centrifugal force is so great, on account of the rapid rotation of the air in the inner rings, that there is practically a calm central core something like 20 or 30 miles in diameter.

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[1] The mathematical treatment of this subject of vortex motion in the atmosphere of the earth can be studied in a series of papers by Bigelow in the *Monthly Weather Review*, 1907, and April and May, 1908.

Since the rotation and the progressive movement are to be added together for the northern and eastern sides of a hurricane approaching the Gulf States from the tropics, their difference should be taken for the southern and western quadrants. And the observed winds actually are greater in the former than in the latter quadrants.

The following computations by Bigelow give some idea of the velocities that obtain in a hurricane on the sea-level plane: On the outer radius, 384 kilometers from the axis, the inward velocity is about 4 meters per second, the tangential velocity is 7 meters per second, and the vertical velocity only 0.0035 meters per second. While on the inner tube, 14 kilometers in radius, the inward radial velocity is 2 meters per second, the tangential 184 meters per second, and the vertical 2.63 meters. On this plane the angle of inflow is 30°, and the total velocity rises from 8 meters per second at the outer radius to 212 meters per second on the inner radius. This vortex is computed to be carrying 1,588,260,000 cubic meters of air upward through each vortex tube per second.

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[1] Imagine each circle projected upward so as to form a cylinder or tube.

The Tornado.—The tornado may be illustrated by the St. Louis storm of May 27, 1896. It is a truncated dumb-bell vortex, cut off at the ground on the plane where the inflowing angle is about 30°. This vortex is much smaller than the hurricane, although of the same type. It is about 1,200 meters high and about 2,000 meters in diameter on the surface. The vortex tubes are shown in Figs. 54 and 55. In these figures can be seen the vortex tubes, geometrically spaced, through each of which the same amount

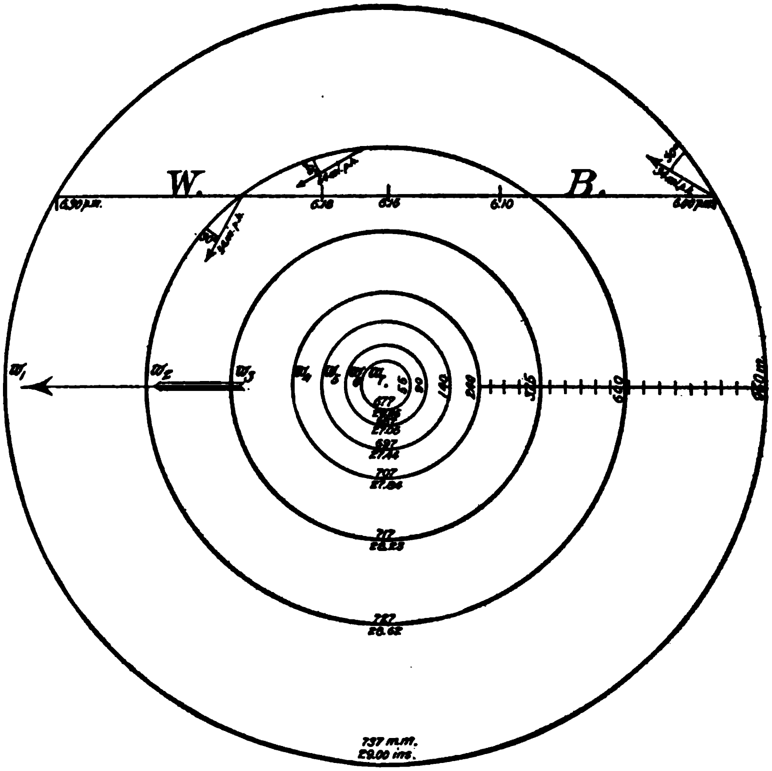

FIG. 54.—HORIZONTAL SECTION OF THE ST. LOUIS, MO., TORNADO OF MAY 27, 1896, SHOWING THE DISTRIBUTION OF PRESSURE AND THE WIND VECTORS. (Bigelow.) W. B.—Locus of the U. S. Weather Bureau station with reference to the vortex.
Scales: Linear, 1 division = 40 meters.
Time, 1 division = 0.7 minute.

of air rises. The rotating velocity is greatest about 300 meters above the ground, but the dimensions are such as to produce enormous velocities in the lower levels. The radius in the outer tube is taken to be 960 meters, and the inner tube 55 meters. The radial inward velocity on the outer tube is —8 meters per second, and on the inner tube —189 meters per second; on the outer tube the tangential velocity is 13 meters per second, and on the inner 224 meters per second; on the outer tube the vertical velocity is 0.27 and on the inner tube it is 80 meters per second. On the outer tube the total velocity is 15 meters per second and on the inner tube 270 meters per second. The volume of air ascending in each tube is 774,500 cubic meters per second. On account of the distortion of the theoretical vortex, due to the cutting of the lower portion by the truncated plane, and to the progressive motion of the whole system that constitutes the tornado, there is difficulty in computing the pressure to fit these observed velocities and radii.

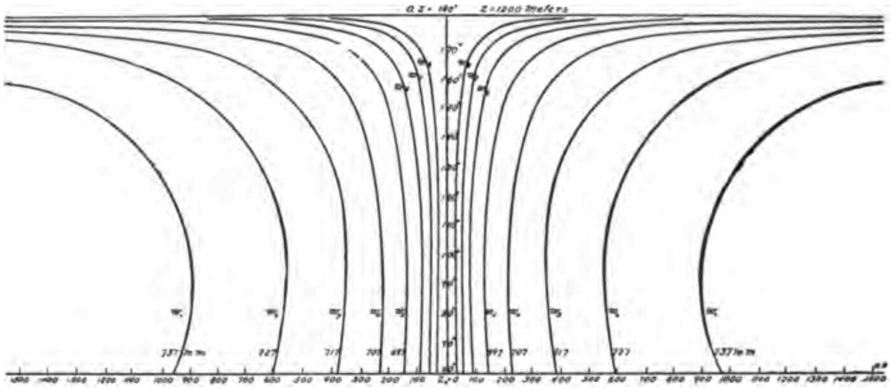

FIG. 55.—VERTICAL SECTION OF THE ST. LOUIS, MO., TORNADO OF MAY 27, 1896, SHOWING THE VORTEX TUBES IN A THEORETICAL, TRUNCATED, DUMB-BELL-SHAPED VORTEX.

Tornadoes occur in the southern and southeastern quadrants of areas of low pressure, along the borders of the cold and the warm masses which entered into the structure of the cyclone. When a cold mass is superposed upon a warm mass, as was the case at St. Louis, a tornado will occur if the difference in specific gravity be sufficient to inaugurate a violent mixing, and the rotation be about a vertical axis, instead of about a horizontal axis, as in the case of thunderstorms.

Waterspouts.—There are two forms of vortices that develop into tornadoes and waterspouts of small dimensions. The St. Louis tornado described above was a comparatively large vortex of the dumb-bell-shape type. At Cottage City, Mass., on August 19, 1896, there developed a series of waterspouts of which good photographs were secured (Fig. 56), that have enabled Bigelow to study this vortex with considerable precision.

The waterspout vortex is a long, thin tube of the dumb-bell-shape type, about 1,200 meters high and 600 meters in diameter near the cloud. The vortex tube that is visible appears to be about 200 meters wide and to have a slightly smaller diameter just below the middle plane between the sea level and the clouds, showing that the vortex is truncated by the sea-level plane, which cuts off the full development of its lower parts.

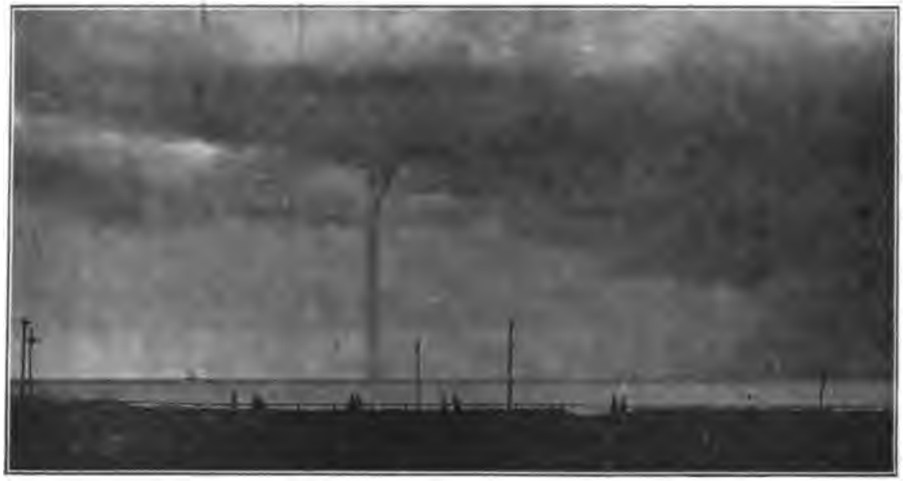

Fig. 56.—Waterspout, Cottage City, Mass., August, 1896.

The tubes are arranged on a geometrical ratio, and each tube carries 16,451 cubic meters of air per second upward through each vortex ring. At the sea level, at a point 200 meters distant from the center, the inward radial velocity is —11.3, the tangential velocity 2, and the vertical velocity 0.13 meters per second. On the seventh tube 12 meters from the axis, the inward velocity is —194, the tangential 34, and the vertical velocity 39 meters per second. This great velocity may, by coming in contact with the sea, draw in the water, raise it to a height of several hundred meters, and by centrifugal force discharge it outward again, thus making the beautiful cascade which surrounds the base of the tube. On the land the tornado tubes are always surrounded by a cloud of dust and débris that are drawn in at the bottom and thrown outward at the higher levels, from which they fall in the quiet air back to the ground.

There is another kind of vortex, called the funnel-shaped vortex, that is frequently developed in small tornadoes and waterspouts. The upper half of Fig. 57 is similar to the *funnel*-shaped vortex. In this vortex the radial velocity is directed outward from the sea level to the cloud and increases upward with the height. The tangential velocity is maximum at the sea level for every tube and decreases upward with the height until it vanishes at the cloud base. The tangential velocity increases greatly with the approach of the axis to the tubes. The vertical velocity decreases upward with the height until it vanishes at the cloud level; it also increases greatly in passing from the outer tube toward the axis.

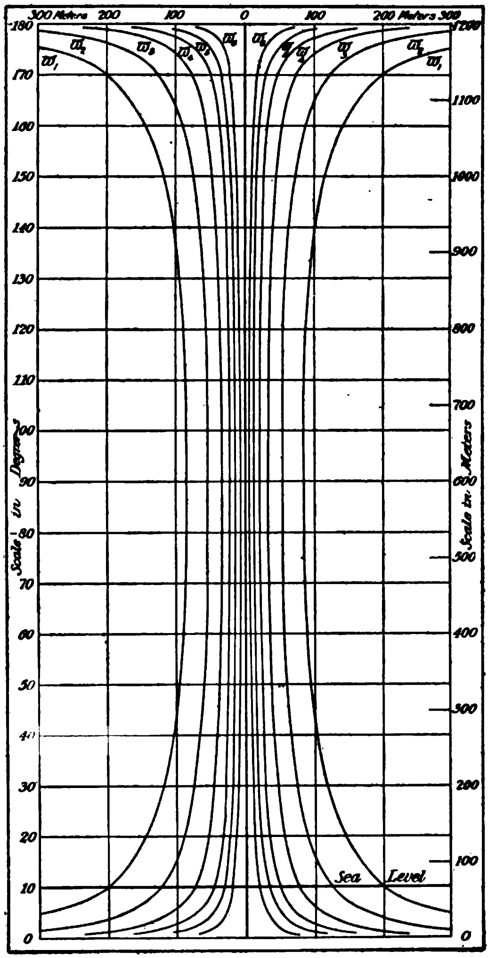

Fig. 57.—Tubes in the Funnel-shaped Vortex

On the sea level, at a distance of 18 meters from the axis, the radial velocity is 0.020, the tangential velocity is 22.1, and the vertical velocity 2,444 meters per second. At 2 meters from the axis the radial velocity is 0.214, the tangential velocity is 2,354, and the vertical velocity is 277 meters per second. It thus becomes possible for a velocity of 364 meters per second to occur on the inner tube near the sea level, so that the air rotates in $\frac{1}{25}$ of a second. The volume of air ascending upward through each vortex is 2,468 cubic meters per second. This enormous velocity indicates that tornadoes of this class, although comparatively small in dimensions, have immense destructive power near the axis, as can be seen by the effects along the tracks that have been laid waste by the rotating air as the tornado advances.

Thunderstorms.—The thunderstorm, so familiar to everyone, may be defined as a local rain accompanied by lightning, thunder, gusts of wind, and, frequently, hail. It lasts but a few minutes or an hour at any one spot, but evidently moves slowly across the surrounding country. Its approach is heralded an hour before its arrival by dark clouds piled up in the horizon and perhaps a half hour before by the mutterings of distant thunder.

On land thunderstorms occur most frequently at specific hours of the day or night, such as 3 to 5 in the afternoon or 9 to 10 in the evening, and sometimes even at 2 or 3 A.M., but no such diurnal period is observed in midocean. The phenomena usually occur in a pretty regular order of succession. After several hours of fair weather, with gentle winds, there comes a calm; the cumulus clouds grow larger, the lower stratum of clouds is seen to be moving rapidly; gusts of wind start up with clouds of dust, rain is seen to be falling at a distance; the movement of rain and dust shows that the wind is blowing out from this rain cloud near the ground no matter which way the rainy region is advancing; a few large drops fall from slight clouds, and then suddenly the heavy rain begins. Lightning that may have occurred during the preceding few minutes becomes more frequent and more severe as the rain increases. After the maximum severity of rain and wind, the lightning also diminishes or entirely ceases, and we are soon able to say that the storm has passed by. If we watch its retreat from us in the afternoon we shall see the rear of a great cumulus on which the sun is shining, but through whose dark-blue curtain of cloud and rain nothing save occasional lightning is visible. After the storm has passed, the lower atmosphere soon becomes appreciably cooler and drier, the sky is nearly clear of clouds, and the wind has shifted to some other point of the compass than that which prevailed before the storm.

LOCATION OF THUNDERSTORMS ON WEATHER MAP.—If we examine the daily weather maps in connection with local thunderstorms, we shall find that these occur far more frequently in the southwest and southeast quadrants of a region of a low barometer than they do in the northwest and northeast quadrants. The first summer's work of the U. S. Weather Bureau gave the forecaster frequent occasion to publicly state that he divided thunderstorms into three classes:

(*a*) Those that are sporadic, apparently caused by special regions of warm air dotting the large areas of high pressure and clear sky.

(*b*) Those that occur in regions of southerly winds southeast or northeast of the central " low," caused probably by the deflection of these surface winds upward by hills or shore lines or by their convergence toward the head of a bay; conditions that stimulate the formation of large cumulus clouds.

(*c*) Those that occur south or southwest of the low center and are located on the front or advancing edge of an extensive mass of cooler or drier, and therefore denser air, which is slowly descending from the upper atmosphere and underrunning or lifting up the warmer and moister air in front of it. These latter are the most intense of all thunderstorms.

(*d*) There is a fourth unimportant class, in which the thunder is faint and the lightning rarely seen and never injurious. These occur mostly in the winter season in connection with snowstorms.

THUNDERSTORM PRESSURE WAVES.—One of the most instructive series of studies of thunderstorms has been that pursued by E. Durand-Gréville, of France. By drawing isobars for very short intervals, such as every hundredth of an inch, between stations near each other, he has been able to show that the wind gusts and thunderstorms of Class (*c*) occur along a narrow band of steep barometric gradients south and east of the main center of low pressure, which he calls the thunderstorm zone, or, more properly, the zone of wind gusts, or close-grained isobars, meaning thereby all gusts, including those that attend a thunderstorm. This is evidently also the zone that marks the front of the advancing wave of dense air underrunning and lifting up warm or moist air. When this wave passes there is a decided rise or jump in pressure and a falling temperature. Barograph records show that the pressure increases suddenly and markedly as this front passes, and afterwards suddenly but slightly several times, as though successive smaller masses of heavy air were abruptly pushed along. These projections on the barogram are sometimes called "thunderstorm noses." They move along from station to station as regularly as the winds and clouds themselves, and, in fact, as the whole thunderstorm.

LIGHTNING.—The terrific lightning that often accompanies the thundercloud is especially severe in the interior of the rain storm. The origin of this lightning, which is nothing but an intense oscillating discharge of electricity, is still problematic. We know that the air and its vapors are charged with electricity, and one may often see sparks pass between a series of clouds and at the same time between the two extreme clouds and the ground, so that there can be no doubt that different adjacent masses of air can be in different electrical conditions, but we have never yet been able, in the physical laboratory, to reproduce these conditions closely enough to feel assured that we fully understand the mechanism of the thundercloud.

As to the origin of the electricity or the electrification, it is quite plausible that there may be some minor processes at work, such as friction, the discharge of vapors from volcanoes, chemical activity, induction, etc., but our attention is at present directed principally toward two sources: (*a*) The bombardment and ionization of the outer atmosphere by electrified corpuscles or electrons issuing at great velocities from the sun. This theory has been developed by Strömer, Birkeland, Arrhenius, and others, and has much in its favor. (*b*) The electrical separation supposed to be produced by the breaking of large raindrops into smaller ones by an uprushing current of air. This theory, advanced by Simpson,[1] is supported by observations and numerous laboratory experiments, and deserves careful study.

In regard to the electric phenomena of the atmosphere, it is not safe to hazard definite statements, but possibly auroras are due to earth-captured solar electrons, while the lightning of a thunderstorm owes its origin, chiefly, at least, to the electrical separation produced by the action of wind on raindrops.

BIBLIOGRAPHY

ABBE, CLEVELAND, "The Mechanics of the Earth's Atmosphere, a Collection of Translations," Washington, 1891. (Smithsonian miscellaneous collections, 843.) Translations of papers by Hagen, Helmholtz, Kirchhoff, Oberbeck, Hertz, Bezold, and Margules, and reprints of papers by Rayleigh and Ferrel.

BIGELOW, FRANK H., "Report on the International Cloud Observations," Washington, 1900. (United States Weather Bureau, *Report of the Chief*, 1898–99, vol. ii.) Includes comparative study of the contributions of Ferrel, Oberbeck, Sprung, Hertz, Bezold, etc., and a proposed uniform system of fundamental constants and formulæ.

BRILLOUIN, MARCEL, "Mémoires originaux sur la circulation générale de l'atmosphère," Paris, 1900. Comprises translations and abstracts of the principal contributions of Halley, Hadley, Maury, Ferrel, Werner Siemens, M. Möller, Oberbeck, and H. von Helmholtz.

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[1] *Philosophical Transactions Royal Society*, Series A, vol. ccix, pp. 379–413, 1909.

FERREL, WILLIAM, " A Popular Treatise on the Winds; Comprising the General Motions of the Atmosphere, Monsoons, Cyclones, Tornadoes, Waterspouts, Hailstorms, etc., etc.," New York, 1889 (and later reprints).

HILDEBRANDSSON, H. HILDEBRAND, AND TEISSERENC DE BORT, LÉON, " Les bases de la météorologie dynamique. Historique—État de nos connaissances," Paris, 1898—. 3 vols. Comprehensive history of the development of dynamic meteorology and review of the data on which it is based. In course of publication.

CHAPTER X

THE WINDS OF THE GLOBE

Anemographs.—For a detailed study of atmospheric circulation instruments are necessary that will record both the direction and the velocity of the wind. For simply *indicating* the direction, wind vanes are almost universally employed. In Fig. 58 is shown a vane designed to *record* the direction of the wind. The vane itself is supported on friction rollers, shown at *h* in the detailed drawing. A slender rod supported by the same rollers extends downward inside the support, and has clamped upon it at *e* four cam collars, so arranged that with the vane pointing toward one of the cardinal points of the compass an electric circuit is closed through the corresponding spring. The cams overlap and are so set that when the wind vane points NW, NE, SE, or SW, the circuit is closed through two springs. A circuit closer on the clock of the register, shown in Fig. 59, Weather Bureau meteorograph, completes the circuit through the proper magnet or magnets once each minute, and the record shown at *a, a,* Fig. 60, results. The record sheet is wrapped around the register cylinder, as shown in Fig. 59, and the cylinder is revolved by the register clock at such a rate that the transverse parallel lines on the record sheet represent five-minute intervals of time. The position of the dots at *a, a,* Fig. 60, represents the direction from which the wind was blowing. Thus, the record shows that the wind was quite steady from the south until 4.35 P.M., when it changed successively to the SE, E, NE, N, and NW, and then back to the N, NE, and E. These variations in direction were caused by the passage of a thunderstorm. The record at *c* shows that the sun was shining continuously until 3.11 P.M., and the record at *d* that rain commenced at 4.41 P.M., and continued until 5.23 P.M.

Anemometers.—A great variety of instruments are available for recording the velocity of the wind. A common form is the Robinson anemometer shown in Fig. 58. It consists of four hemispherical cups attached to cross arms and mounted on a spindle, near the lower end of which is an endless

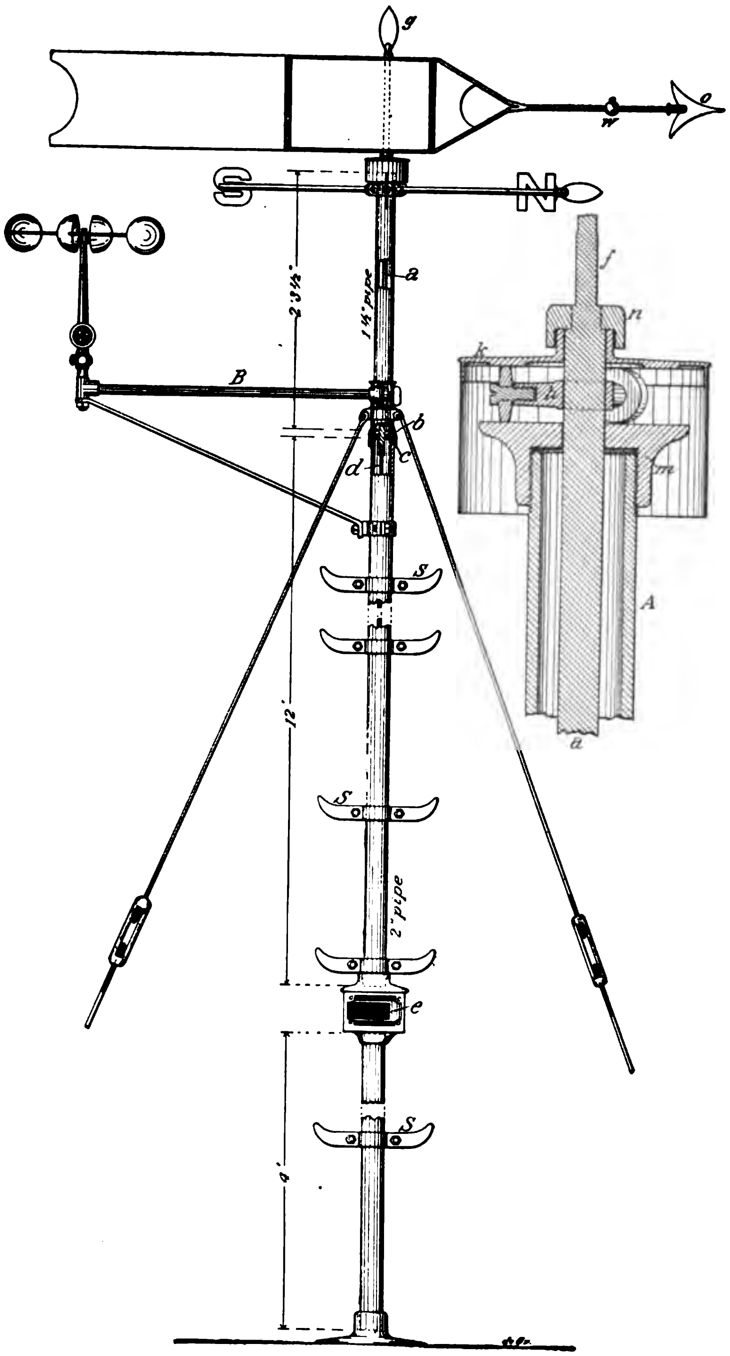

FIG. 58.—STANDARD 18-FOOT WIND VANE AND ANEMOMETER SUPPORT.

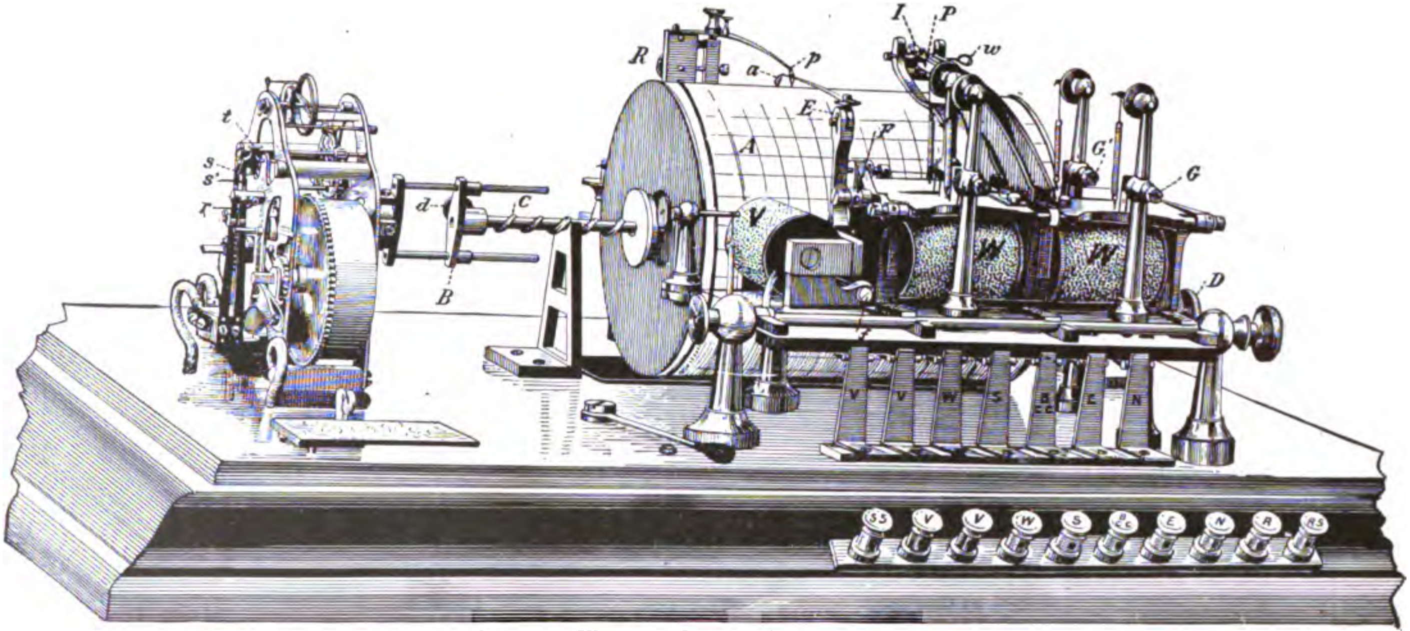

FIG. 59.—WEATHER BUREAU METEOROGRAPH.

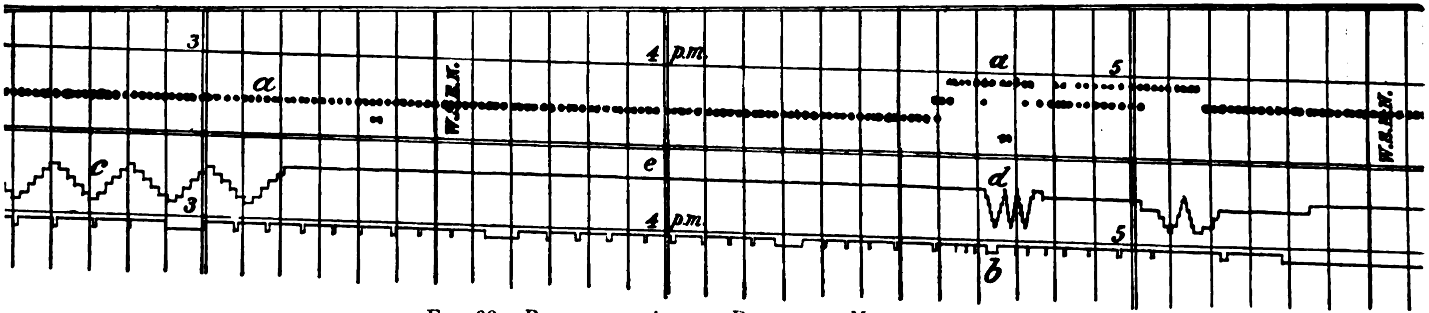

FIG. 60.—PORTION OF ACTUAL RECORD OF METEOROGRAPH.

screw that engages one of a series of gears so arranged that the rapid rotation of the cups and spindle is made to slowly rotate a dial wheel. On the face of this dial are ten pins. As the dial is turned these pins successively press down a contact spring, closing the circuit through the magnet *V* on the meteorograph (Fig. 59), and producing the record shown at *b* in Fig. 60. In this record each dentation of the line represents a mile of wind, except that to facilitate counting the ninth and tenth dentations are combined in one long dentation.

The record in Fig. 60 shows that between 3 and 3.25 P.M. the dentations were almost exactly five minutes apart. That is, the wind was blowing at the rate of 12 miles per hour. At 4.39 P.M., which was just before the beginning of rain in a thunderstorm, the dentations were about a minute apart, which represents a wind velocity of 60 miles per hour.

These recorded velocities are based upon the supposition that the centers of anemometer cups revolve with a velocity equal to one third of the velocity of the wind. Marvin[1] has shown that for ordinary gusty winds the relation between wind and cup velocities is not so simple, but is better expressed by the equation

$$\log V = 0.509 + 0.9012 \log v,$$

in which $V =$ the velocity of the wind and $v =$ the velocity of the cups. Table XXVI shows the relation between velocities recorded by the Weather Bureau pattern of the Robinson anemometer, which are the velocities published in all Weather Bureau reports, and the wind velocities as computed by the above equation.

TABLE XXVI.

Wind Velocities, as Indicated by a Robinson Anemometer, Corrected to True Velocities.
(Miles per hour.)

INDICATED VELOCITY.	+0	+1	+2	+3	+4	+5	+6	+7	+8	+9
0	......	......	......	......	......	5.1	6.0	6.9	7.8	8.7
10	9.6	10.4	11.3	12.1	12.9	13.8	14.6	15.4	16.2	17.0
20	17.8	18.6	19.4	20.2	21.0	21.8	22.6	23.4	24.2	24.9
30	25.7	26.5	27.3	28.0	28.8	29.6	30.3	31.1	31.8	32.6
40	33.3	34.1	34.8	35.6	36.3	37.1	37.8	38.5	39.3	40.0
50	40.8	41.5	42.2	43.0	43.7	44.4	45.1	45.9	46.6	47.3
60	48.0	48.7	49.4	50.2	50.9	51.6	52.3	53.0	53.8	54.5
70	55.2	55.9	56.6	57.3	58.0	58.7	59.4	60.1	60.8	61.5
80	62.2	62.9	63.6	64.3	65.0	65.7	66.4	67.1	67.8	68.5
90	69.2	......	......	......	......	......	......	......	......	......

NOTE.—Corrections need not be applied below velocities of 11 miles per hour, where fractions of miles are not desired.

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[1] *Circular D*, Instrument Division, U. S. Weather Bureau, Third edition, p. 16.

It is often desirable to know the pressure exerted by the wind. From experiments conducted by the Weather Bureau it has been found that the relation between the wind velocity and the wind pressure may be expressed by the equation

$$P = 0.0040 \frac{B}{30} V^2,$$

where $P =$ the pressure in pounds per square foot of surface exposed normally to the wind direction, $B =$ the height of the barometer in inches, and $V =$ the corrected true wind velocities given in Table XXVI. Table XXVII gives the wind pressure corresponding to the velocity of the wind *as recorded by Weather Bureau anemometers.*

TABLE XXVII.

Wind Pressures (Pounds per Square Foot).

INDICATED VELOCITY.	+0	+1	+2	+3	+4	+5	+6	+7	+8	+9
0	......	......	......	......	......	0.104	0.144	0.190	0.243	0.303
10	0.369	0.433	0.511	0.586	0.663	0.762	0.853	0.949	1.05	1.16
20	1.27	1.38	1.50	1.63	1.76	1.90	2.04	2.19	2.34	2.48
30	2.64	2.81	2.98	3.14	3.32	3.50	3.67	3.87	4.04	4.24
40	4.44	4.64	4.84	5.07	5.27	5.51	5.72	5.93	6.18	6.40
50	6.66	6.89	7.12	7.40	7.64	7.88	8.14	8.43	8.69	8.95
60	9.22	9.49	9.76	10.1	10.4	10.6	10.9	11.2	11.6	11.9
70	12.2	12.5	12.8	13.1	13.5	13.8	14.1	14.4	14.8	15.1
80	15.5	15.8	16.2	16.5	16.9	17.3	17.6	18.0	18.4	18.8
90	19.2	......	......	......	......	......	......	......	......	......

When no instruments are available for measuring the wind velocity, as is generally the case at sea, it may be approximately estimated by means of the scale given in Table XXVIII:

TABLE XXVIII.

NAME.	Miles per Hour.	Apparent Effect.
Calm	0	No visible horizontal motion to inanimate matter.
Light	1 to 2	Causes smoke to move from the vertical.
Gentle	3 to 5	Moves leaves of trees.
Fresh	6 to 14	Moves small branches of trees and blows up dust.
Brisk	15 to 24	Good sailing breeze and makes whitecaps.
High	25 to 39	Sways trees and breaks small branches.
Gale	40 to 59	Dangerous for sailing vessels.
Storm	60 to 79	Prostrates exposed trees and frail houses.
Hurricane	80 or more.	Prostrates everything.

Pressure anemometers of various kinds have been devised by means of which the varying velocity of the wind can be continuously recorded. A record made by the Dines pressure-tube anemometer is shown in Fig. 61. During gales it is the sudden gusts of excessively high velocity that cause most damage.

Anemometers and wind vanes are available only for recording the direction and velocity of the wind near the surface of the earth. Most of our knowledge of the movement of the upper-air currents is derived from a study of the clouds.

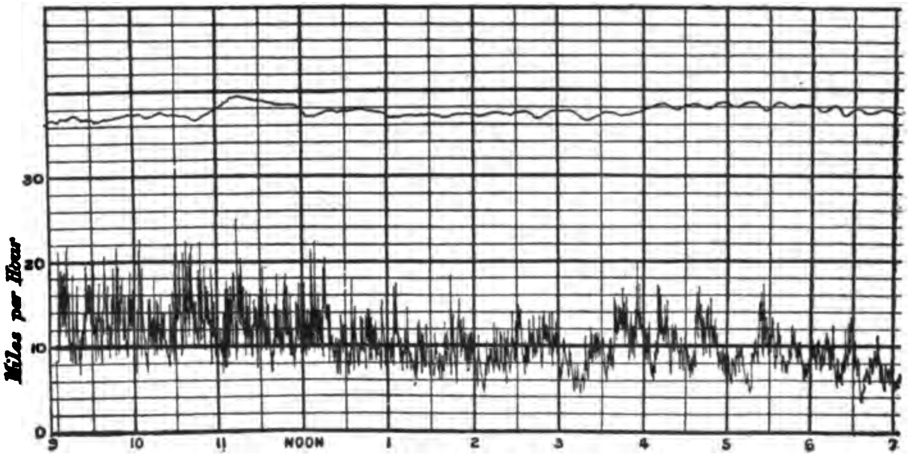

FIG. 61.—WIND VELOCITY RECORD BY THE DINES PRESSURE-TUBE ANEMOMETER.

Classification of Winds.—The winds of the globe may be grouped under three general headings, as follows: Permanent winds, periodic winds, and nonperiodic winds.

To the permanent winds belong the trade winds, the antitrades, and the prevailing westerlies of high latitudes; to the periodic winds belong monsoons, land and sea breezes, and mountain and valley breezes; to the nonperiodic winds belong the high winds that accompany cyclones and anticyclones, including the hurricane of the West Indies, the typhoon of the China Seas, the simoom of Arabia and Africa, the sirocco of Italy, the föhn winds of the Alps, the chinook winds of the northwestern part of the United States, the mistral of Europe, the Texas northers, the blizzards and the hot winds of our western plains, tornadoes, thunderstorm gusts, whirlwinds, and many others.

PERMANENT WINDS.—These are the winds of the general circulation unmodified by local conditions. Their general features have already been outlined, and they will now be considered in greater detail.

Trade Winds.—Probably the best known of the permanent winds are the so-called trade winds on each side of the equator. While of only moderate intensity, these winds are remarkable for their steadiness as regards both direction and velocity, particularly over the oceans. Originating in each hemisphere in the high-pressure belts at about latitudes 30° north and south, they blow toward the equator, being deflected more and more toward the west as they advance. Between them, nearly under the equator, is a belt of light and irregular winds, known as the calm belt, or the doldrums. Probably there is a slight residual motion toward the west in this belt. At the polar limits of the trade winds, and coinciding with the crests of the high-pressure belts in each hemisphere, are two other calm belts. While the doldrums, particularly over the oceans, are characterized by high humidity and almost daily rains, these latter belts have a low humidity and little rain. These are in the region of descending air currents, while the doldrums are in the region of the most active ascending currents.

The position of these calm belts, and of the equatorial and polar limits of the trade winds, is not fixed, but varies with the season of the year. They move northward and southward with the sun. Neither must it be supposed that these belts of calms, and the northeast and southeast trade-wind belts, follow certain parallels of latitude entirely around the globe. This is more nearly the case in the southern than in the northern hemisphere. In both hemispheres they are more uniform over the oceans, as shown in Charts 17 and 18.

On Chart 17, for January and February, it is seen that the trade-wind belts approach very close to each other in both the Atlantic and the Pacific oceans on a fairly well-defined line just north of the equator, except in the vicinity of the larger islands of Australasia, where the northeast trades extend several degrees south of the equator, and, indeed, to the continent of Australia, although they have become so feeble and irregular as to have lost the characteristics of trade winds. In the Indian Ocean the northeast trades also cross the equator. On Chart 18, for July and August, it is seen that the line of meeting has moved north of the equator about 5°, except in the Indian Ocean and north of Australasia, where the northeast trades are entirely obliterated. This annual swing of the doldrums corresponds very closely with the annual movement of the heat equator.

The calm belts corresponding to the ridges of high barometric pressure at the polar limits of the trade winds are less clearly defined. On Chart 17 in the northern hemisphere a calm belt may be traced across the Atlantic at about latitude 32°. In the Pacific Ocean it is irregular in its course, and it does not exist on the China coast. In the southern hemisphere there is a cyclonic area over the Atlantic Ocean at about latitude 30°, at the center and on the south side of which there are light and variable winds, while on the north side there are strong and steady winds. This is due to the fact that on one side the cyclonic circulation augments the trade winds, while on the other side it opposes them. In the Pacific Ocean the southeast trades are everywhere quite feeble and irregular except off the west coast of South America, and there is no well-defined calm belt at their polar limit, although beyond latitude 40° the prevailing westerlies increase rapidly in force.

During July and August, as shown on Chart 18, the southeast trades of the Pacific are highly developed, and there is a well-marked calm belt at their polar limit, about latitude 25°, which extends on this parallel across the Atlantic, and part way across the Indian Ocean. In the northern hemisphere two great anticyclonic whirls cover the Atlantic and the Pacific oceans, with light winds at their centers at about latitude 32°, and bands of comparatively light wind extending east and west near this parallel.

It is thus seen that in each hemisphere the trade winds are most highly developed during its cold season. It has already been noted that at this season the high-pressure belts at latitude 30° are also the more pronounced.

The Antitrade Winds.—This name is usually applied to the winds from the west in the upper atmosphere, their direction of motion being nearly opposite to that of the trade winds at the surface. There is evidence, however, that above the doldrums, in the region where upward convection is strongest, the winds are toward the west, decreasing to zero velocity at about 6 miles. The dust from the great volcanic outbreak of Krakatoa in 1883, latitude 6° south, encircled the earth from east to west in fifteen days. Near the equator the cirrus clouds move generally toward the west, while observations by means of kites and balloons have shown the presence of this current up to a height of about 6 miles. Near the Cape Verde Islands, latitude about 16° north, the direction of the upper currents is toward the northwest. Near the Canary Islands, latitude about 28° north, the direction is toward the northeast. These changes in direction accord with the deflecting effect of the rotation of the earth on its axis.

The Prevailing Westerlies.—In high latitudes in the southern hemisphere the winds blow from the west with a persistency comparable with that of the trade winds, and with much greater force. In high latitudes in the northern hemisphere the winds, while often of great force, are variable as to their direction because of the frequency of the occurrence of cyclones and anticyclones in these latitudes, which, during their passage over any district, dominate the wind direction, often to the complete obliteration of the prevailing winds at the surface. However, when these winds are resolved into their components, as has been done in the discussion of cyclones and anticyclones, after subtracting the cyclonic and anticyclonic components from the actual wind movements a persistent current from the west becomes apparent (see Chapter IX).

PERIODIC WINDS.—The above discussion of surface winds applies more particularly to the ocean. Over the continents further complications are encountered, which are readily understood when we note the relation between the seasonal variations in wind direction, pressure distribution, and temperature anomalies. In certain regions, as India, the east coast of Africa, the north coast of Australia, and in Texas, there is almost a complete reversal of wind direction from winter to summer, while in other regions, as in Spain, or the northern coast of South America, and on the Pacific coast of the United States, there is a decided seasonal change in wind direction, although it does not amount to a reversal. Similarly, diurnal variations in temperature produce diurnal variations in wind direction.

The Monsoon.—The influence that seasonally deflects the wind from its normal direction is called the monsoon influence,[1] and the resulting winds are called monsoon winds.

In India is found the most complete development of the monsoon winds. During the winter months, with a high-pressure area overlying the continent of Asia, with the equatorial belt of low pressure a few degrees south of the equator in the Indian Ocean, and lowest over the continent of Australia, the northeast trades prevail over India and the adjacent seas with great steadiness, but with only gentle force. Since they blow from a cold mountainous region to a tropical sea-level country they are very dry.

In summer the interior of Asia is covered by a great area of low barometric pressure, so that there is a continuous gradient from latitude 30° south to northern India and Afghanistan. In consequence the southeast trade of the southern hemisphere is deflected and continued as a southwest monsoon of great intensity, extending well into the interior of Asia. Since it blows from a tropical sea, and against the high Himalaya Mountains, copious precipitation results, and the liberation of the latent heat of condensation still further augments the wind velocities.

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[1] See "The Winds of the Globe," by James H. Coffin, Smithsonian Institution, Washington, 1876.

There are several reasons why the monsoon influence in Australia is much weaker than in Asia. It lies principally in the tropics; it is smaller than Asia; and it is without high mountains. Its seasonal variations in temperature, and therefore in wind direction, are slight when compared with those of Asia, so that the winds, on the whole, hardly accomplish a reversal of direction. In July and August, when the continent is slightly cooler than the surrounding ocean, there is a tendency for the winds to blow outward from all sides, but especially from the northern coasts, since the monsoon influence then augments the prevailing southeast trades. These winds cross the equator, are deflected to the northeast, continue as southwest winds along the Asiatic coast, and are finally drawn into the interior of the continent by the low-pressure area overlying it, thereby causing a seasonal reversal of the winds of the Asiatic coast as far north as latitude 60°.

In January and February, when the continent of Australia is warmer than the surrounding ocean, the tendency is for the winds to blow in from all sides. This brings rain-bearing winds to the eastern and southern coasts, since the monsoon influence there simply deflects or else augments the prevailing winds. On the northern coasts, where the monsoon opposes the southeast trades, the resultant inflowing winds have not sufficient force to penetrate far inland.

The interior of Africa is always warmer than the surrounding oceans, and the tendency is therefore for inflowing winds throughout the year. The east coasts of northern Africa are somewhat under the Asiatic monsoon influence. On the west coast the southeast trades are deflected throughout the year, and blow as southwest winds from the sea to the land. In the interior of Central Africa there is a considerable zone where the winds blow from the north in winter and from the south in summer, due to the shifting of the doldrums, and the equatorial limit of the northeast and southeast trades, with the annual march of the sun, an effect that is noticeable in other tropical countries.

South America is likewise warmer than the ocean throughout the year, but the temperature difference is more marked in summer than in winter. In the northern part there is a reversal of wind direction from southeast in July to northeast in January, due partly to the increased monsoon influence during the hot month, and partly to the southward swing of the doldrums at that season of the year. This reversal also covers nearly all of Brazil, which is in the region of the southeast trades. The monsoon effect is no doubt here magnified by the excessive precipitation on the Andes Mountains.

Over the eastern part of the United States the prevailing northwest winds of winter become southwest in summer, and on the west Gulf coast the northeast trades of winter become southeast in summer. This latter is purely a monsoon effect, augmented by the topography of the country, the surface of which rises gradually from the Gulf to the Rocky Mountain region. West of the Rocky Mountain region the onshore winds of summer have a strong offshore component in winter, due to the area of high pressure that overlies the plateau region.

The monsoon influence in Europe is not marked, except on the mountainous Spanish peninsula, which has inflowing winds in summer and outflowing winds in winter.

Land and Sea Breezes.—Closely allied to the seasonal monsoons are the diurnal land and sea breezes. Unlike the monsoons, which may influence the climate of the greater part of a continent, land and sea breezes do not extend far inland. As the temperature of the land rises from increasing insolation during the morning hours, the air near the surface expands. In consequence there is a flow of air in the upper levels out over the sea, increasing the surface pressure there, and causing a surface flow of air in toward the land. This flow will be maintained until the land cools off after sundown, when a reverse circulation will be established. As the air over the land cools and contracts, air aloft flows in from the sea, increasing the surface pressure over the land, and causing a surface current from the land to the sea, which is usually gentle as compared with the sea breeze.

In general, land and sea breezes are strongest where the diurnal range of temperature is greatest, as within the tropics, or in temperate zones during the summer. They are greatly modified by the local topography. As is the case with monsoon winds, they are generally strongest where the land rises gradually from the shore back into the interior, except that the sea breezes are influenced by the surface contour on the immediate coast rather than by the topography of the entire continent. In nearly inclosed harbors, surrounded by mountains or hills of considerable height, the land and sea breezes will be greatly augmented. The heated air on all the slopes will rise, and will be replaced below by a strong current through the mouth of the harbor. Similarly, at night the cool air from the surrounding mountain slopes and valleys will drain into the harbor and pass out at its mouth with a suddenness and force that may be dangerous to small vessels.

Land and sea breezes are, as a rule, gentle, and are only noticeable in periods of calm or of light wind. When strong winds prevail from other causes the land and sea breezes simply modify somewhat their direction and speed. An offshore wind will be weakened by day and strengthened by night, while winds parallel with the coast will be deflected diagonally, toward the land by day and toward the sea by night.

Land and sea breezes are often pronounced on small, mountainous islands, and also on the shores of great inland lakes. The climate of Chicago is considerably modified by sea breezes from Lake Michigan. These are the most marked in summer, as during the spring months the prevailing winds at all hours of the day are from the cold lake to the warmer land, as shown by Fig. 62, while during the late fall and the winter months the prevailing westerlies, which are land winds, are but little modified by the warm waters of the lake. In Fig. 63 are shown the prevailing direc-

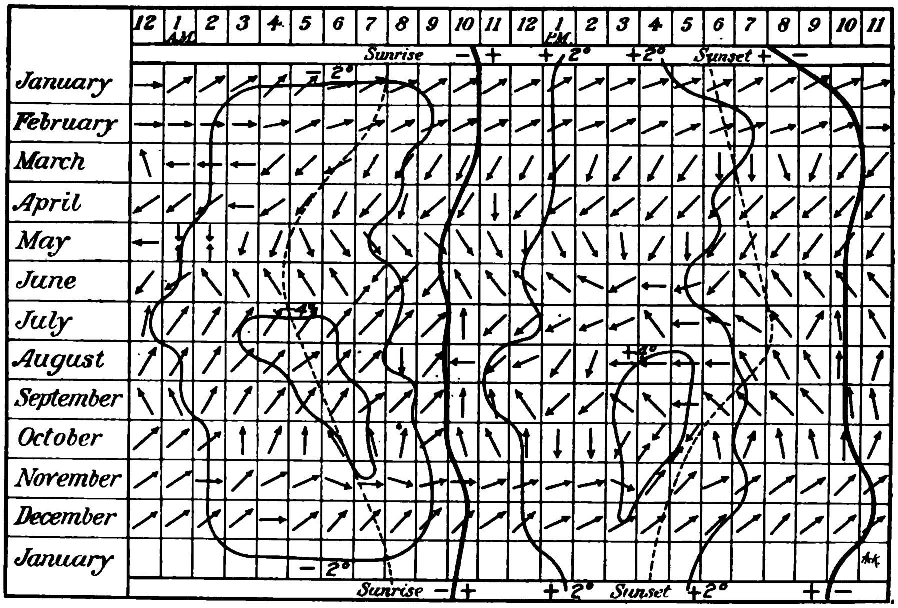

FIG. 62.—PREVAILING-WIND DIRECTION AND DEPARTURE OF MEAN TEMPERATURE AT CHICAGO, ILL., FOR EACH HOUR.

tions of the wind for each hour of the day and for the four months June, July, August, and September. It is seen that at about noon the morning southwest wind is replaced by a northeast wind off the lake. The result is that the temperature, which had been rising rapidly, remains nearly stationary during the afternoon. This is brought out on Fig. 62 by the lines showing the departure of the hourly temperatures from the mean for the day. These lines also show the effect of the increasing frequency of land breezes in autumn. The + departures during the afternoon hours are noticeably higher after August.

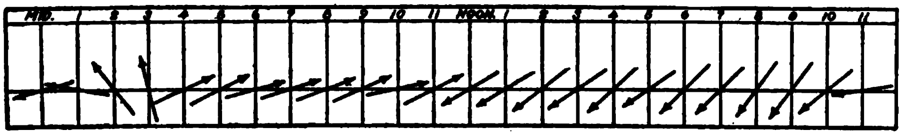

FIG. 63.—LAND AND LAKE BREEZES AT CHICAGO JUNE TO SEPTEMBER, 1882.

As we go back from the lake front the effect of the lake breezes rapidly diminishes, so that they are hardly noticeable ten miles inland. With a low barometric area to the north or northwest of the lake region, prevailing southwesterly winds are greatly strengthened, so that the lake breeze is not able to overcome it, and Chicago then experiences a hot day.

Mountain and Valley Breezes.—Similar in nature to the diurnal winds just described are mountain and valley breezes. These are best developed where deep valleys open out on broad plains. We will consider the effect of the diurnal rise in temperature on a horizontal air stratum at some elevation above the plain. This stratum will be elevated by the expansion of the air below it, and the expansion will be greater over the plain than in the mountain valley, because of the greater depth of air to expand. The elevation will be least where the horizontal air stratum joins the surface of the ground in the valley. Gradients will thus be formed in the atmosphere from over the plain toward the valley, causing an upper air current in that direction, which will be deflected upward by the configuration of the ground.

It is probable that both these causes operate to produce mountain and valley breezes. The temperature of the ground in elevated valleys must be greater than the temperature of the air on the same horizontal level, and the air in the valley will therefore tend to rise as the air current from over the plain approaches it. At night the surface of the mountain becomes comparatively cold, and the dense air on its surface is drained by gravity through the valleys to the plains below. When the valleys are narrow, or several converge into a gorge, the wind thus formed may become strong. The breezes from the mountains are usually stronger than the breezes from the plains.

On broad, gentle slopes this air drainage has an important effect upon the occurrence of frosts. The flow of cold air from the hilltops to the valleys and plains below causes frosts to occur in the lowlands before they do at higher elevations. The point least liable to frosts may be found halfway down the slope. Here the drainage is at a maximum without the cooling of elevation experienced on the summits.

NONPERIODIC WINDS.—The variations in wind direction corresponding to the different sections of cyclonic and anticyclonic areas, with the accompanying changes in temperature, have already been studied. Sometimes geographical features produce local peculiarities in winds from certain directions. Since cyclones and anticyclones recur at irregular intervals, are of variable intensity, and do not always pursue the same paths, the winds produced by them, unlike those already studied, are nonperiodic. Some of these winds are directly traceable to the passage of cyclones or anticyclones. In other cases the relation is not so immediately apparent.

Föhn Winds.—This name is applied to a warm wind that sometimes blows down a mountainside for a few hours or days at a time. It is found in all mountainous parts of the world, but has been most studied in the Alps, and on the eastern slope of the Rocky Mountains in North America, where it is called the Chinook wind. It is most common in winter and spring, as the vertical temperature gradient is then the least. It is remarkable for the rapidity with which it evaporates snow from the surface of the ground.

In Switzerland föhn winds usually occur when an area of low pressure is approaching Europe from the Atlantic, causing winds from the south to cross the Alps. At first the air in this south wind appears to be drawn from levels above the tops of the mountains. As it descends their northern slopes its temperature rises 0.99° C. for each 100 meters of descent, which is about the adiabatic rate. Since the average vertical gradient on the north side of the Alps is less than half as great (0.45° C. per 100 meters), it follows that each 1,000 meters of descent of the air currents will cause a rise in temperature of 5.4° C. as compared with the average temperatures.

If the low-pressure area persists over western Europe, air will be drawn up to the southern slopes of the Alps from the lower levels. As it rises, much of the moisture will be condensed and precipitated, thereby liberating the latent heat of condensation, so that the temperature of the air when it reaches the crest of the mountains is comparatively high. It descends the mountain as a dry wind, and in consequence is warmed at the rate above given. Since the temperature of this air current when it left the Mediterranean region was already high as compared with the temperature of central Europe, the rise in temperature will be even greater than above indicated.

Föhn winds are most marked, both as to temperature and velocity, in valleys with a SE–NW or a S–N trend, as these directions coincide with the wind directions on the front of a cyclonic area. They also sometimes occur in valleys on the south side of the Alps, when an area of high barometer covers western Europe and there is a low area over the Mediterranean. They are never so intense as the föhns of the northern valleys.

Chinook Winds.—In North America when an area of low pressure crosses the Canadian Rockies, it causes winds from the Pacific to cross the mountains in its southern quadrant. These cause copious rains or snows on the western slopes of the mountains, and hot, dry winds to the east of them. Since the prevailing winds of this region are from the west, these winds at certain seasons become almost permanent, and exert a marked influence on the climate, which is particularly noticeable in the Saskatchewan valley in Canada and in portions of Montana and Wyoming in the United States, where the winters are noticeably milder than on the corresponding parallels farther east. The valleys are generally free from snow, so that stock can live on the ranges practically the entire year.

In Fig. 64 is reproduced a thermograph trace from Havre, Mont., for January 22–26, 1907. On the evening of the 22d an area of high barometer with low temperatures was central over Minnesota. A low was central to the northwest of Havre, and it passed to the northeast during the night. The wind changed from northeast to west, increased in velocity from 2 to 36 miles per hour, and was accompanied by a rise in temperature from $-2°$ to $+36°$ F. at midnight. During the afternoon of the 23d the low moved to Nebraska, and an area of high pressure approached Havre from the northwest, becoming central over that station at 8 P.M. of the 24th, the surface winds at this time being from the west. A minimum temperature of $-33°$ occurred on the morning of the 25th, but during the day the barometric gradient became such as to cause a general movement of the atmosphere from west to east, and the temperature rose to $+10°$ without any change in the surface wind direction.

While the effects of the chinook winds are most marked in the valleys on the eastern slopes of the Rocky Mountains, they are sometimes felt 500 miles to the east of them. They are also noticeable as far south as Colorado. We should expect to find traces of their influence in the vicinity of all extensive mountain ranges outside the tropics.

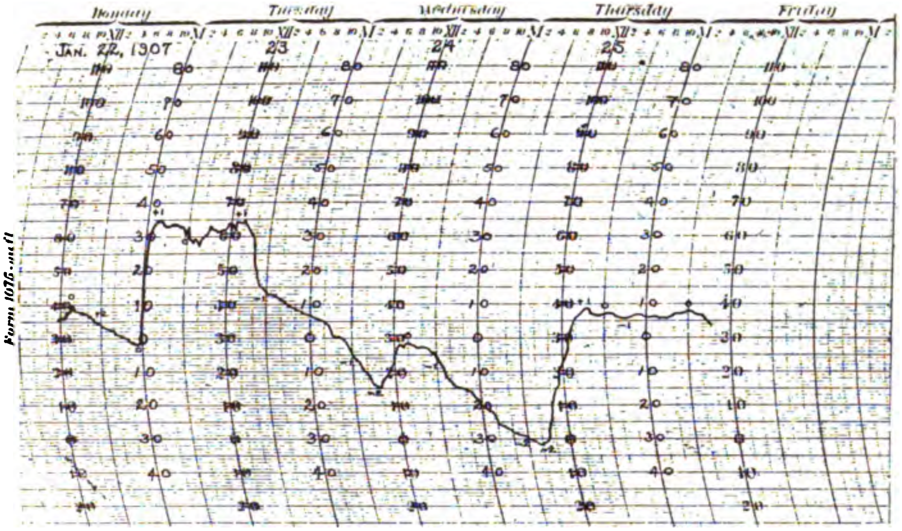

FIG. 64.—THERMOGRAPH TRACE FROM HAVRE, MONT., JANUARY 22–26, 1907.

Sirocco, or Hot Winds.—This term, which is of Italian origin, appears originally to have been applied to a south wind blowing from northern Africa to southern Europe. On the African coast it is hot, dry, and dust-laden, and if it persists for many days vegetation is destroyed. By the time it has reached the coast of Europe it has become laden with moisture, and in consequence is very depressing. It occurs on the front of low-pressure areas. Davis, in his "Elementary Meteorology," extends this name to include all warm winds on the front of a low-pressure area, such as the "hot winds" of our western plains, the leveche of Spain, the harmattan of Africa, the leste of Madeira, the khamsin of Egypt, the brickfielder of New South Wales, and the zonda of Argentina, these last two being from the north. Hann[1] shows that some of the characteristics of the sirocco are due to föhn influences.

The hot winds of our western plains appear to be purely cyclonic winds. In a cloudless sky the surface of the earth becomes very hot, and in turn imparts to the air above it a temperature of 100° F. or more. If the wind continues for several days it evaporates the moisture from the soil, and vegetation in consequence is parched.

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[1] "Handbook of Climatology," Part I (translated by Ward), p. 362.

Mistral, or Cold Winds.—After the passage of an area of low barometer over southern Europe in winter, the advance of an area of high pressure over northern Europe frequently causes cold northerly winds to penetrate to the Mediterranean. In southern France they are called the mistral, and on the Adriatic Sea the bora. A similar wind, except that it is from the south, is called the pampero in Argentina, and the southerly burster in Australia. The Texas norther also belongs to this class.

After the passage of a low-pressure area from the region of the Gulf to the Atlantic coast an area of high pressure sometimes appears in the upper Missouri or Mississippi valley. The result is a steep barometric gradient from the north to the south. In addition the usual winter temperature gradient is augmented, since the cyclone has caused warm south winds over the Gulf States, while the anticyclone has caused an inflow of cold air from the north. Furthermore, the topography of the country favors air drainage from the north to the south. The result is a cold northerly wind, which is especially severe over Texas, sometimes causing a fall in temperature comparable with the rise in temperature that accompanies the chinook. This wind may or may not be accompanied by rain or snow. Similar winds usually herald the advance of the familiar cold waves of the central valleys and the Atlantic coast. In the Dakotas this wind is sometimes accompanied by blinding snow, which, combined with the extreme cold, makes it especially destructive to animal life. It is locally called the blizzard. The buran and the purga, which occur on the steppes of central Asia, have the characteristics of the blizzard.

The above-described winds are typical of many others that might be named.

Hurricanes, typhoons, tornadoes, simooms, and thunderstorm gusts are discussed in other chapters.

BIBLIOGRAPHY

Marvin, C. F., "Anemometry," 3d ed., Washington, 1907. (United States Weather Bureau, *Circular D,* Instrument Division.)

Ferrel, William, "A Popular Treatise on the Winds," New York, 1889 (and later reprints).

Statistics of wind direction for stations in all parts of the world are to be found in J. H. COFFIN'S "The Winds of the Globe," Washington, Smithsonian Institution, 1875; A. BUCHAN'S "Report on Atmospheric Circulation," *Challenger* report, Physics and Chemistry, vol. ii, Pt. 5, London, etc., 1889; and SUPAN'S "Statistik der unteren Luftströmungen," Leipzig, 1881. The latest statistics of wind direction and force over the oceans are given by means of "wind roses" on the marine meteorological charts ("pilot charts") of the U. S. Weather Bureau, U. S. Hydrographic Office, British Meteorological Office, and Deutsche Seewarte, Hamburg.

CHAPTER XI

THE CLOUDS

How Clouds are Formed and their Classification.—The term clouds, as used in this chapter, refers to an aggregation of fine, visible particles of condensed water vapor usually formed and floating in the atmosphere.

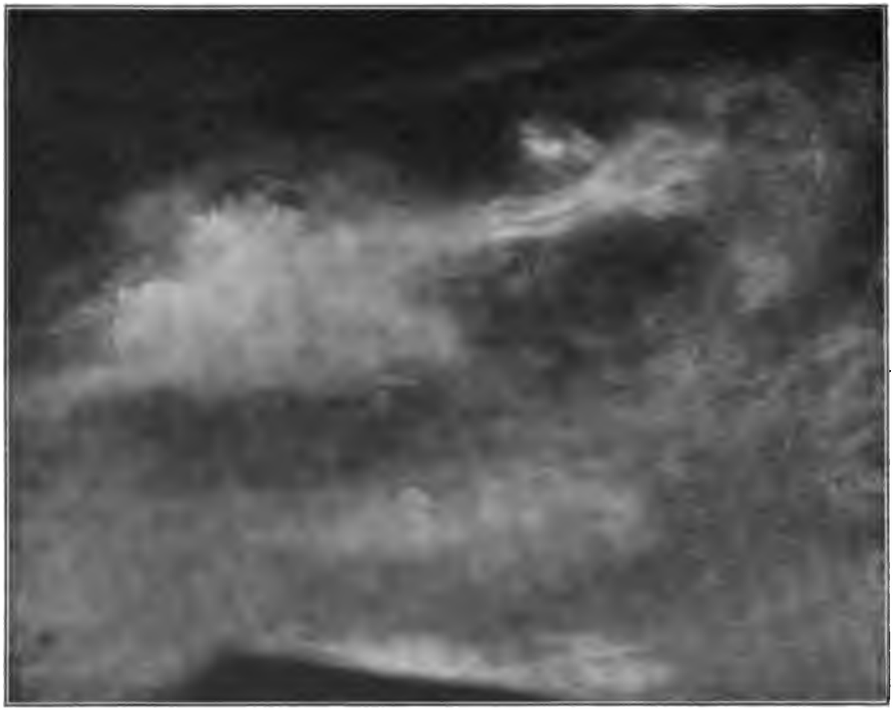

FIG. 65.—CIRRUS (Henry).

A cloud differs from a fog in its method of formation and usually in its position, and from a mist or rain in the size and number of its particles. However, they merge the one into the other so gradually that no rigid division is possible.

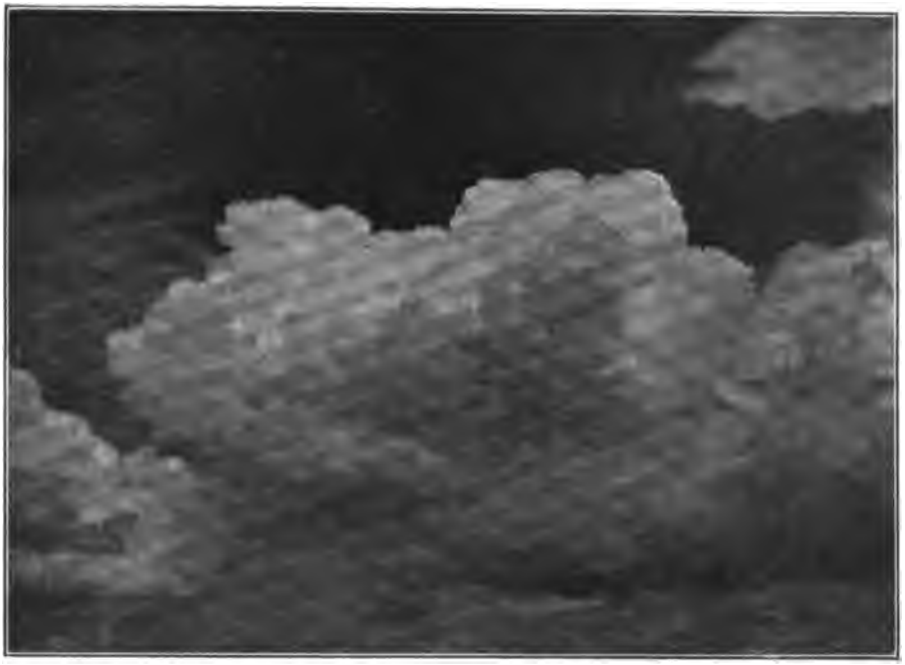

FIG. 66.—CUMULUS (Henry).

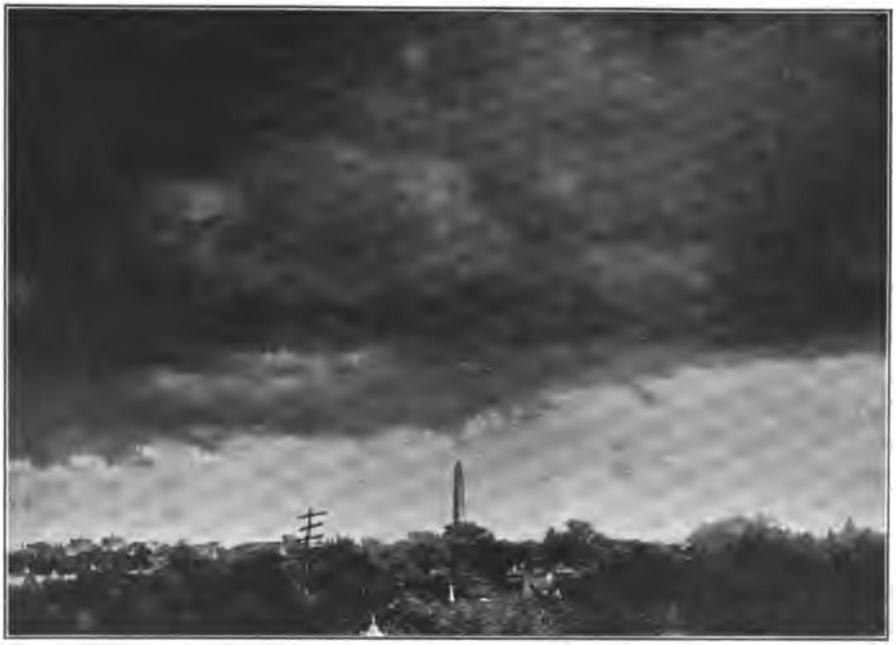

FIG. 67.—STRATUS AND STRATO-CUMULUS (Henry).

Masses of dust and of smoke caught up and carried along by the winds are often called clouds because of their appearance only, and are therefore purposely excluded by the above definition.

A careful study of clouds is of importance to the meteorologist, because from them comes nearly all our precipitation of whatever nature, because they largely modify the distribution of insolation, and because their forms, their altitudes, and their velocities furnish information in regard to the relation of wind currents to different classes of storms; all of which is of the greatest use to the forecaster.

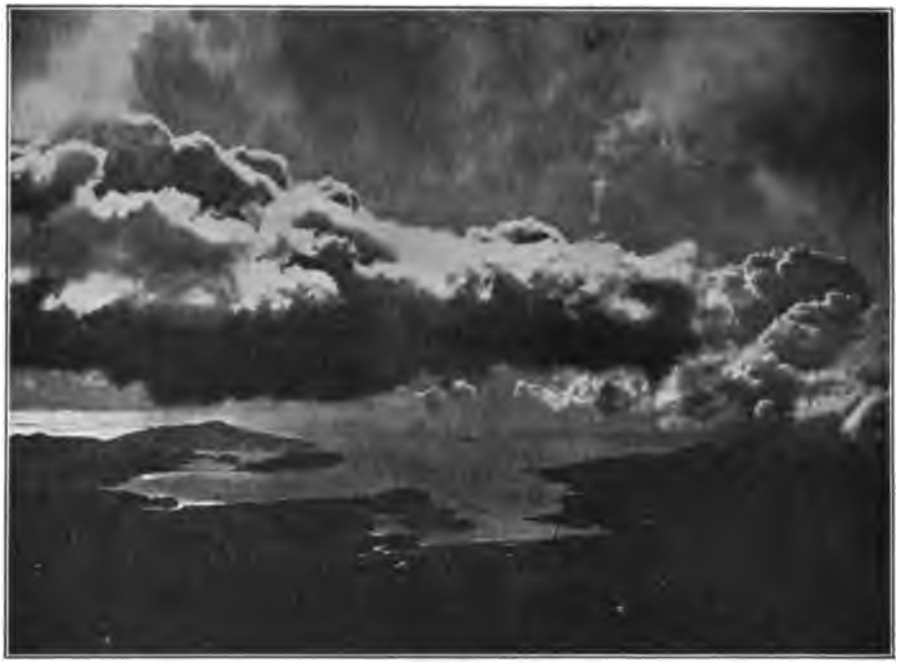

FIG. 68.—FOG RISING AND FORMING CLOUD (McAdie).

Several interesting cloud forms are characteristic of certain localities and bear local names. Thus in southern California we have the tremendous thunder clouds known as "sonoras." In England we have the Helm and the Bar of the Crossfell, whose formation was explained by Espy, and at Cape Town the Tablecloth that hangs over the mountain so artistically. In 1857 Sir John Herschel, the eminent astronomer, called attention to the fact that when the south or southeast wind blows most strongly and the Tablecloth is most perfectly developed, the wind that curls over and sweeps down the north side of the mountain gathers up the dust from the streets of Cape Town, rebounds and forms the small cloud that is almost stationary over the jetty or landing docks about two miles farther on. In every way this small cloud is analogous to the Bar at Crossfell; and there are many similar ones at different places on the globe. In general we know that an ascending current of air is liable to lead to the formation of a cloud, either a small one near the ground, as in these cases, or an immense cumulus such as often accompanies a thunderstorm.

A proper beginning of the study of clouds was made in 1802 by Dr. Luke Howard, of London, when, as a result of several years of observations, he formulated a system of nomenclature.

Dr. Howard recognized first the light, high clouds as cirrus, the heaped-up thunderclouds as cumulus, and the horizontal layers that cover the lowlands as stratus.

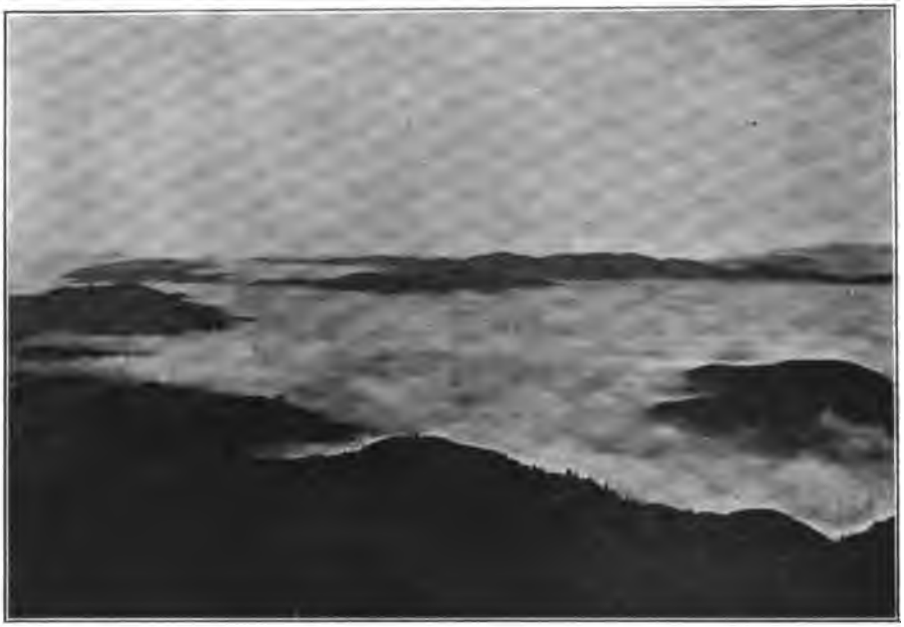

Fig. 69.—Fog in the Valley (McAdie).

Two modifications of these he named the cirro-cumulus and the cirro-stratus. Then to two more complex compositions he gave the terms cumulo-stratus and cirro-cumulo-stratus.

Figs. 65, 66, and 67, from photographs by Prof. A. J. Henry, illustrate Howard's three fundamental forms—cirrus, cumulus, and stratus. Figs.

68, 69, and 70 represent fog billows, photographed by Prof. A. G. McAdie from the summit of Mount Tamalpais, California.

James P. Espy, about 1825 to 1830, while living in Philadelphia, taught that air as it rises cools by expansion until it reaches the dew point, and after this by condensation of its moisture forms a visible cloud warmer than it would otherwise be by reason of the latent heat set free when steam is condensed into water. His ideas were not generally accepted by European meteorologists until Sir William Thomson (now Lord Kelvin) showed that it was not the mere act of expansion that caused the air to cool, since, as Espy himself had found out, an expansion into a vacuum did not produce any cooling.

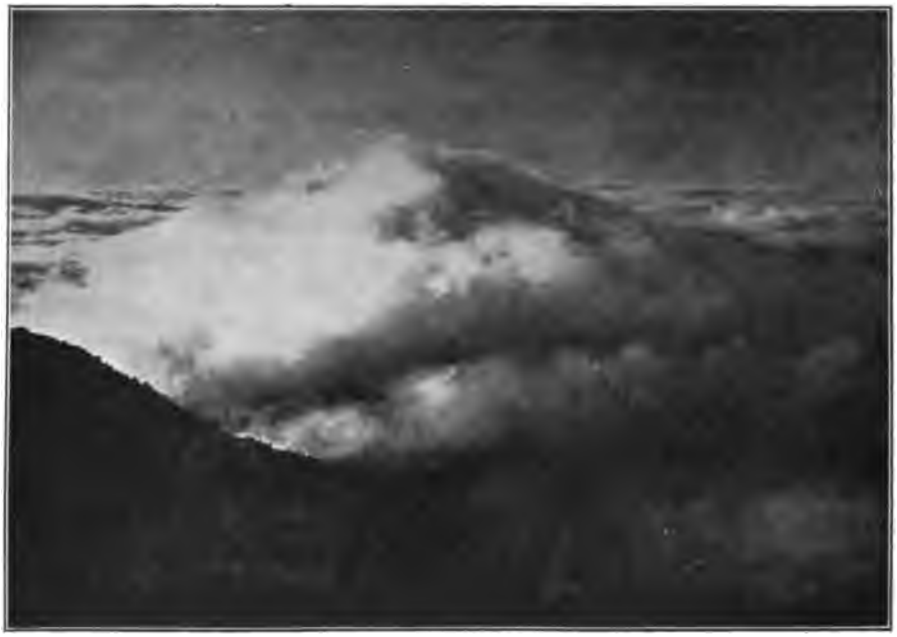

FIG. 70.—VIEW OF FOG FROM MOUNTAIN.

Sir William proved that the cooling which converts steam into a cloud as it escapes from a boiler, like the cooling that produces a natural cumulus in moist air, is due to the work done by the expansion of the steam and air against the general pressure prevailing at the time and place. Hence for a given volume expansion, *greater cooling* and correspondingly denser clouds occur lower down where the pressure is greater, and more work must be done than higher up in the atmosphere.

After the invention of the balloon it was soon learned that the cloud particles are not hollow vesicles or bubbles of water, nor always spheres of water, but often spheres of water cooled far below freezing, which, whenever they touch anything, immediately turn into crystals of ice.

Measuring the Height of Clouds.—The method of measuring the altitudes of the clouds depends upon the available observers and apparatus. Thus two observers half a mile apart, connected by telephone, agree upon some small cloud to be observed at a given moment. At that moment each one points his telescope at the cloud, clamps the vertical and horizontal circles, and then at his leisure reads off the angles. Evidently, if we know the distance (see Fig. 71) *A B* and the angles *a* and *b* we can determine the altitude *C D* either graphically or trigonometrically.

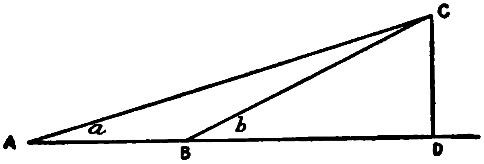

Fig. 71.

A better method is to use photogrammeters, first-class photographic cameras mounted on surveyor's transits (see Fig. 72). At a prearranged moment simultaneous photographs of the cloud and its surroundings are taken. Each sensitive plate shows, in addition to the cloud, a pair of horizontal lines crossing at its center *O*. Suppose both cameras had been tipped up at the same elevation, then the camera at *A* would show the cloud *E F* at a lower point of its plate than would the camera at *B*, and this difference can be read off by a scale of degrees. When the cameras are unequally tipped a corresponding correction must be added. We thus get the angles at *A* and *B* not merely for one point of the cloud, but for every point and for every cloud that is shown on the plate; in other words, we can determine the dimensions of the cloud, and by still another pair of pictures taken a few minutes later, we can determine all the motions that are visible on its surface.

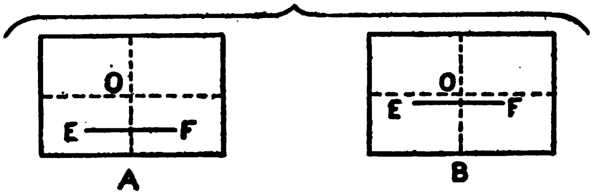

Fig. 72.

Where only one observer is available there are other practicable methods; the simplest of these was probably first employed by an Italian about two hundred years ago. The observer being on an elevated spot and having a good map of the landscape before him, draws thereon a short line to represent the path described by the shadow of the cloud during a short space of time—say thirty seconds; he may do this for several clouds, so as to assure himself that all are moving parallel to each other and with uniform velocity. He now looks upward and observes the angular velocity of one of these clouds as it passes through the zenith. We will perceive, as shown in Fig. 73, that he has determined the horizontal distance *O H* equal to *Z K*, and the corresponding angle *ZOK* in a vertical right-angle triangle, so that the distance *O Z* is fixed, since there is only one place where *Z K* will fit in. The distance *Z O* may be determined geometrically by graphic construction of the triangle, or may be computed trigonometrically as before. Of course this method is not applicable to very high and diffuse clouds. For these a special method was devised by another Italian, who observed them at sunrise or at sunset, when the sun's rays graze the earth at *H* (see Fig. 74) and illumine the cloud at *K;* the observer at *O* notes the angle *ZOK* between the zenith and the cloud, and the time which gives the angle *HCO* by which the sun is below the horizon. Although the computation is complicated, yet it is perfectly possible to compute *K E,* which is the height of the cloud above the earth.

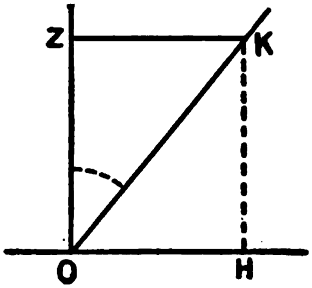

Fig. 73.

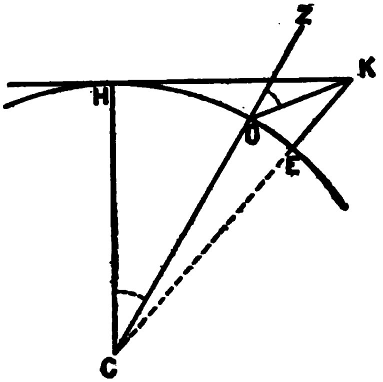

Fig. 74.

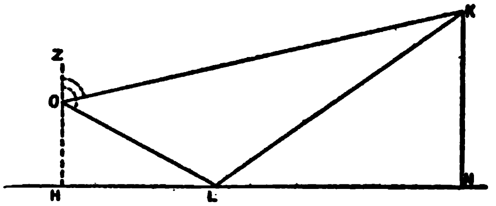

Fig. 75.

Oftentimes an observer standing on a hill looking down into the bosom of a smooth lake sees the clouds reflected therein (Fig. 75), and can observe the angle *ZOL,* as also the angle to the cloud itself, *ZOK;* if he knows his own altitude above the lake—namely, $O\,H$—he has all the data needed for computing the height of the cloud $K\,N$.

Perhaps the most interesting case is that of an observer on board ship, or, in fact, on any moving vehicle. In this case the computations are quite laborious, but, as the observer is sure of the point which he observes, the method has some advantage over those in which two observers are employed. On a ship, however, owing to the rolling and pitching of the vessel, the observer must be furnished with a special instrument, known as the marine nephoscope, which rests on top of the standard ship's compass and keeps its surface very near the horizontal.

A nephoscope is simply a circular mirror M (Fig. 76) and a point P with two degrees of freedom, one in planes parallel to the mirror, the other in planes at right angles to it.

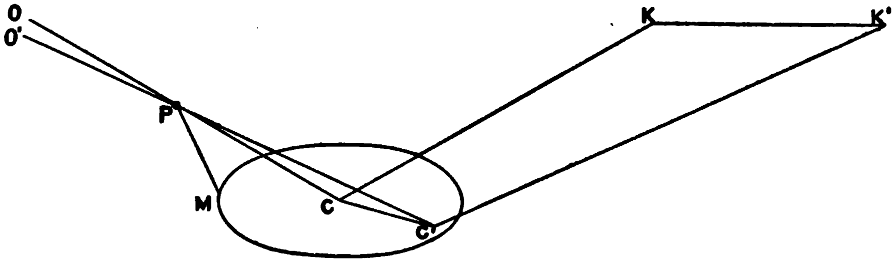

FIG. 76.

The observer places his eye at O and sees at the center C the reflection of a definite part K of the cloud right behind the point P. When K has moved to the point K', the reflected ray from it through the stationary point P will be seen at O'. The observer must read the compass bearing and length of the line $C\,C'$ and record the number of seconds required for the cloud to travel the distance $K\,K'$. Now this bearing and the time depend not only on the motion of the cloud, but also on the motion of the ship; when the latter is changed the resultant is different. A pair of such observed resultants, together with a knowledge of the corresponding directions and speeds of the ship, gives the data necessary for computing the true motion of the cloud and its true altitude. This elegant method was first used by a Swedish meteorologist about 1888 and almost simultaneously and independently of him by Professor Abbe, of the U. S. Weather Bureau.

Mysterious Clouds of Great Altitudes.—Certain clouds that are seen about midnight in summer have for twenty years past received considerable attention from Abbe and others, but as yet we do not know enough about them to give them a name; sometimes they are called nacreous, from their gentle, pearly luster, at other times noctilucent, because they shine at night; they have as yet only been observed in northern latitudes during the month of June and above the northern horizon. The most reasonable assumption is that they are so high up as to receive a little light from the twilight then prevailing over the Arctic regions. Otherwise they may be self-luminous or phosphorescent.

A few measurements have given these clouds altitudes of between 20 and 40 miles. But we believe that a more systematic search for such clouds and a more careful determination of their altitudes must be made before we can attempt to discuss the questions that will naturally arise in regard to them, for of course at present no one can understand how aqueous vapor can be carried up to those altitudes or exist there long enough to form a visible cloud. The eruption of Krakatoa did throw vapor particles up to middle altitudes, and these formed interesting optical phenomena, but not visible clouds. However, if such clouds do exist, and their motions can be determined, we shall hardly dare to assume that the motions represent any movement of the atmosphere as such, for the air is so rarefied that the cloud particles may be moving without reference to the wind.

BIBLIOGRAPHY

CLAYDEN, ARTHUR W., "Cloud Studies," London, 1905.

CLAYTON, H. HELM, "Observations Made at the Blue Hill Meteorological Observatory. Discussion of the Cloud Observations," Cambridge, Mass., 1896. (*Annals of the Astronomical Observatory of Harvard College,* vol. xxx, Pt. IV.) Includes an extensive history of cloud nomenclature.

INTERNATIONAL METEOROLOGICAL COMMITTEE, "International Cloud Atlas," Paris, 1896. In French, English, and German. Colored plates. This is the official international classification of clouds, adopted by all countries; but several more detailed classifications, based upon this, have been proposed by cloud specialists.

VINCENT, J., "Atlas des nuages," Bruxelles, 1907. (*Annales de l'Observatoire royal de Belgique, Nouvelle série, Annales météorologiques.*)

Plates illustrating the International Cloud Classification are published by the U. S. Weather Bureau.

CHAPTER XII

PRECIPITATION

WATER exists in the atmosphere in various forms: it falls from the clouds as rain, snow, or hail; it collects on cold surfaces as dew or frost. We cannot see very far into or through a cloud or fog, because the minute spheres of water or crystals of ice are large enough and close enough together to obstruct the beam of light, but we may see quite well through a mile of hazy air when the particles of water are very small or far distant from each other. In proportion as the particles are smaller and more distant the hazy appearance diminishes. So long as any visible particles of water or any fog are present we consider the air containing the particles or fog to be saturated.

How Fog and Cloud are Sustained in the Air.—Water globules are too heavy to float in the air at a constant elevation; they settle downward slowly against a resistance that depends on their size and on the viscosity of the air. The velocity of fall is such that this resistance is equal to the product of the mass of the falling drops by the acceleration in vacuo due to gravity. Therefore, all particles of water of a given diameter tend to fall at about the same rate, and for very small particles, such as occur in clouds and fog, this rate is so small that the gentlest upward movement of the air keeps them from falling to the ground.

The Amount and the Weight of Water Vapor and its Pressure.—If no particles of water or ice are present in the air the latter may still be just barely saturated by aqueous vapor, but in general the air is more likely to be below saturation. We speak of the air as "ordinary dry air" when some aqueous vapor is present but not enough to saturate it. By using chemical dryers we may absorb practically all of this vapor from a small mass of air and make it almost perfectly dry, and then we say that its absolute humidity is zero grains of water per cubic foot of space. Its relative humidity is also zero, meaning thereby zero per cent as compared with the total quantity the space could contain if just saturated at the given temperature.

The weight of the invisible aqueous vapor required to saturate a unit volume of space increases with temperature and is nearly the same whether or not air is present. This vapor has all the properties of the invisible steam in the boiler of a steam engine, and its outward pressure, or elastic pressure, or gaseous pressure, or static pressure, increases with the temperature. Some idea of these weights, in grains per cubic foot, and pressures, in inches of mercurial barometer, may be obtained from the following figures, taken from the Weather Bureau psychrometric table:

TABLE XXIX.

TEMPERATURE. Degrees Fahr.	Vapor Pressure. Inches of Mercury.	Weight, in Grains per Cubic Foot.	TEMPERATURE. Degrees Fahr.	Vapor Pressure. Inches of Mercury.	Weight in Grains per Cubic Foot.
−40	0.0039	0.050	40	0.247	2.849
−20	0.0126	0.166	60	0.517	5.745
0	0.0383	0.481	80	1.022	10.934
20	0.1026	1.235	100	1.916	19.766

It is evident that if all the water in the atmosphere could be taken from it the barometric pressure would be diminished by the weight of the corresponding column of aqueous vapor extending from the barometer to the upper air limits, but the greater part of this diminution would be due to the humidity of the lower levels. The general law of the diminution of vapor with altitude depends principally on the law of the diminution of temperature.

If all the moisture in the atmosphere were condensed and fell as rain, it would, for our ordinary American climates, give a general rainfall of scarcely 2 inches in depth. But in no storm does anything more than a small percentage of all the atmospheric moisture fall to the ground from the column of air above the rain gauge; whence it is evident that, in order to make up the sum total that is measured in our heavy rains, the winds must supply a continuous renewal of fresh moisture above the station.

The vapor of water being mixed with the gases of the air long since gave occasion for the statement that the atmosphere may be looked upon as an engine in which water is evaporated into warm steam in the tropics and at the ground by the solar heat, but cooled and condensed at the polar regions and in the upper strata by an equivalent radiation to space.

To the meteorologist the most important peculiarity of this aqueous vapor is its great specific and latent heat and its property of changing from an invisible gas to visible water or ice whenever its temperature is sufficiently reduced. This change is called the precipitation of the vapor and results in fog, cloud, rain, hail, snow, dew, or frost, all of which are included collectively and individually under the term *precipitation*, borrowed from chemistry, notwithstanding the fact that only a small portion of this precipitate actually falls to the ground.

The study of the condensation and precipitation of atmospheric moisture leads to innumerable meteorological details, the more important of which must be considered.

The elastic pressure or gaseous pressure of the vapor, added to that of the dry gases of the atmosphere, makes up the total pressure in the free atmosphere as shown by a barometer. That is to say, the total pressure is simply the sum of the several partial pressures *at the barometer.* While the total pressure indicated by the barometer is due to and measures the total weight of all the gases and vapors in a cone of quiescent air above it, the cross section of whose base is equal to the cross section of the mercury in the barometer at its upper surface, and whose sides follow the lines of gravitational force, it is not in general true, nor is it at all true in the case of the atmosphere, that the several partial pressures due to the different gases and vapors at and about the barometer measure the weights of the same gases and vapors above it. Equality between partial pressures and weights would hold if the percentages of the gases present remained constant throughout the atmospheres; but when the percentage of any substance decreases with elevation, the pressure it exerts is correspondingly greater than its own weight. Thus the pressure of water vapor at the surface of the earth is about six times its weight, or sixfold what it would be if the gases were not present.

The Falling Rain Collects Many Foreign Substances.—Although rain is simply the condensed portion of vapor that was evaporated into the atmosphere from the surface of the globe and was therefore at first almost pure, yet it has had abundant opportunity to collect many foreign substances. Interesting objects are washed down from dusty air, such as the pollen of plants and the broken siliceous shells of microscopic life carried by the trade winds and by the harmattans of northern Africa. In the midst of hailstones there are often found larger foreign matters evidently carried upward by powerful winds from regions near at hand. From an agricultural point of view the most important substances in rain water are the nitrates, the ammonia, and the very small percentage of nitric and nitrous acids. It would, however, be a mistake to assume that these nitrogenous compounds are in sufficient quantity to maintain abundant local vegetation. They must be supplemented by the nitrates formed by natural biological processes, such as the action of nitrogen-fixing bacteria and by artificial methods of enriching the soil. The influence of sunshine and wind in decomposing surface rocks by slow weathering is greatly increased by the solvent action of rain water.

Condensation Mainly the Result of Cooling by Expansion Against Surrounding Pressures.—The cooling process by which rain is formed is fundamentally the conversion of its heat into work when a mass of air expands against surrounding pressures. It has sometimes been erroneously stated that ascending air does lifting work by virtue of its ascension and must thereby be cooled; but the fact is that its ascension is due to work done *upon* the rising mass by surrounding pressures and not *by* it. The work done *by* it depends on its expansion and is partly an internal work, but principally the external work of pushing aside the adjacent gases. The amount of work thus done determines the amount of heat required, and therefore the amount of cooling. It matters not whether the air moves horizontally into a region of low pressure or vertically into an upper stratum of low pressure; in either case there is cooling. But horizontal change in position sufficient to reach an isobar of a tenth of an inch lower pressure requires considerable time, and various sources of heat may complicate the phenomenon, whereas a vertical movement of a hundred feet corresponding to a tenth of an inch of barometric pressure requires but a few seconds. A very rapid change, or one in which no outside source of heat interferes, is an adiabatic process, and so far as the upward component is concerned we may say that for unsaturated air an ascent of 100 meters should produce a fall of 1° C. in temperature, or an ascent of 178 feet should produce a fall of 1° F.

This rate of cooling becomes smaller as soon as the air cools to the dew point, since from that time onward the condensation of moisture converting latent into sensible heat acts like an outside source, supplying warmth to the expanding air, and thereby decreasing its rate of cooling. Thus air at usual pressure that is saturated at a temperature of 10° C. cools at the rate of 0.54° C., instead of the 1° C. for unsaturated air, per 100 meters of ascent.

When aqueous vapor condenses directly into snow a still larger amount of heat is given off, and this is particularly noticeable in the formation of hail when the process goes on rapidly in the interior of large cumulus clouds.

Among other forms of precipitation, the most important is snow, which consists of crystals of ice usually arranged in symmetrical form. As these crystals gather in light flocculent masses on the ground the depth of snowfall is from five to twenty times greater than the depth of the equivalent water, and an average factor of ten is widely used for its conversion, although it is always better to melt the snow and omit the use of an uncertain factor.

The formation of rain, hail, and snow may be considered as a continuous process of cooling by expansion, and the most convenient method of representing such coolings is by the use of a diagram known as Hertz's diagram for adiabatic changes in the temperature of moist air. This was published in 1884 and a modified form was published by Neuhoff in 1900. In Hertz's diagram (Fig. 77) we have the temperature set off on a horizontal line and the barometric pressures

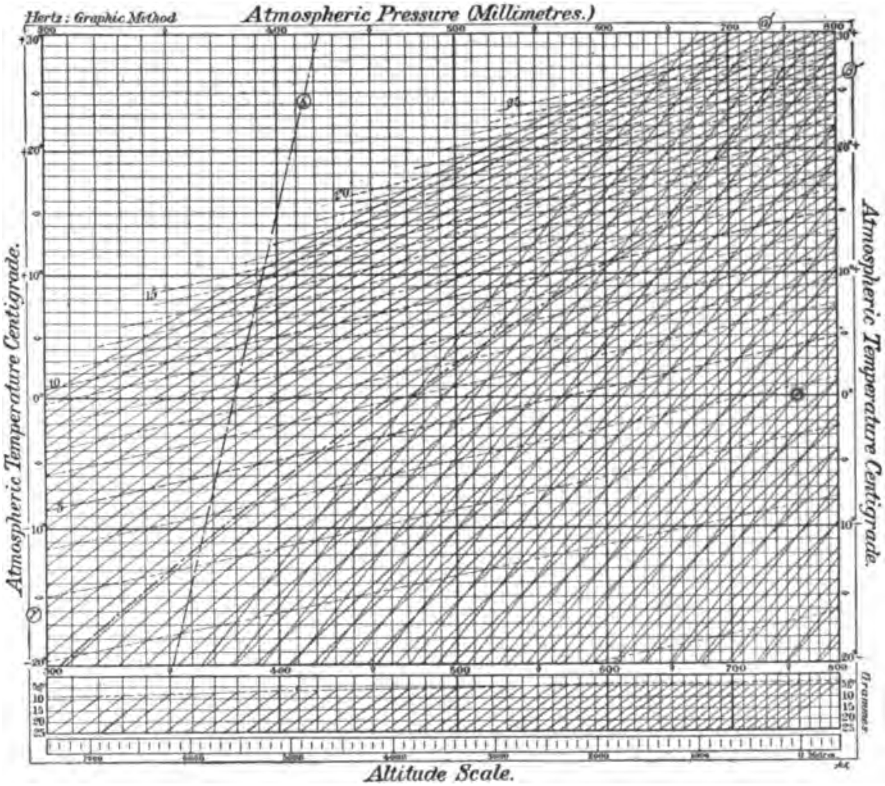

FIG. 77.—ADIABATIC CHANGES IN THE TEMPERATURE OF MOIST AIR (Hertz).

and altitudes measured along a vertical scale. A set of lines called the alpha lines is drawn diagonally to show the rate at which moist air cools as it ascends until condensation begins. Another set of lines drawn across the page at somewhat steeper angle shows a slower rate of fall in temperature after condensation has begun. This set, the beta lines, is interrupted slightly when the lines cross the vertical that represents freezing temperatures, because at this point there begins to be a greater evolution of heat and no temperature fall until all the condensed water in the cloud has changed to ice. For all temperatures below this the cloud is supposed to be composed wholly of snow, and the rate of fall, shown by gamma lines, gradually approaches that due to pure dry air in proportion as we go higher and higher in the atmosphere where the temperatures are lower and the moisture less. For convenience Hertz divides the whole cooling process into four stages—the dry, the cloud, the hail, and the snow stage. The cooling proceeds along the alpha line until the dew point is reached, then along the beta line until the temperature zero Centigrade is reached, along the zero line until all condensed water is frozen, then along the gamma line.

Air Mixing Produces Little Condensation.—The mixing of warm and of cold air together produces slight haze or fog, but not rain properly so called, as was taught by the English meteorologist Hutton, and was, in fact, generally believed until the more correct views of Espy were accepted.

Dew, Frost, and Low Fog Due to Radiation and Not to Cooling by Expansion.—In the formation of dew and frost and low-lying fogs, we have little or nothing to do with cooling by expansion. In these cases the surfaces of the ground and of vegetation cool by radiation, especially to the clear sky. The adjacent moist air also cools by radiation both to the ground and to the sky. It also cools by conduction in so far as it comes in contact with cold surfaces, and then draining away to the lower levels, allows warmer air to take its place and be cooled in turn. Thus radiation, conduction, and convection come into play.

If this process continues, then, as the air cools through the dew point, its moisture begins to deposit primarily on every sharp point and small object, since points and minute particles, because of the large ratio of their surfaces to their volumes, have cooled to the lowest temperatures.

Atmospheric Condensation Begins on Dust Nuclei.—All ordinary atmospheric precipitations begin with the condensation of moisture or vapor on solid dust nuclei. In the midst of a cloud the space between the minute drops is dustless, hence new fog particles or cloud particles do not form therein. Under laboratory conditions of excessive saturation ions, also, may constitute nuclei of condensation.

The study of dust nuclei in the atmosphere was begun by Aitken, but that of ion nuclei has been especially prosecuted by Prof. Carl Barus.[1] The sizes of the nuclei are computed by him from the measured dimensions of coronal rings due to optical interference phenomena. The number of the nuclei occurring in the purest air at Providence, R. I., and the adjacent Block Island indicates a maximum in December or January and a minimum in July or August. Barus further finds that nuclei are not of local origin, but possibly may be of cosmic source, an hypothesis that he is testing by the study of observations made far from any human habitation.

Formation of the Raindrop.—Atmospheric moisture condenses primarily not in hollow bubbles or vesicles, but in small massive spherical particles or spherules with particles of dust as nuclei. The diameters of these spherules of water have been measured. Thus Assmann, on the Brocken, found them to range between 0.006 mm. and 0.017 mm.; Kaemtz, in the fog at Jena, found diameters of 0.014 mm. to 0.035 mm. When the spherules grew to have a diameter of 0.04 mm. the fog or cloud became wet and rain began. The maximum rate of fall of these small particles is very small, owing to the resistance offered by the viscosity of the air. As to the rate of fall of ordinary raindrops at the pressure of 760 mm., Lenard found the following results:

SIZE OF DROP.	Diameter of Drop.	Velocity of Fall.
Small	1.0 mm.	3.0 m. per second.
Large	4.0 mm.	6.0 m. per second.

When the dew-point temperature is decidedly below freezing the particles of water vapor condense directly as crystals of ice, ice needles, or snowflakes. When the spherules are warm and rise into colder air they may cool to 32° F. and change to crystals of ice, or, more frequently, they cool to far below the freezing point without turning to ice. These subcooled[2] water spherules will, however, suddenly turn into ice as soon as they touch one another or any cold solid or liquid surface.

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[1] His first and preliminary memoir is an appendix to the *Report of the Chief of the Weather Bureau*, 1891. His later results have been published by the Carnegie Institution.

[2] Cooled below the freezing point, but not frozen.

When subcooled raindrops strike solid substances they cover these with a coating of transparent ice, but when ordinary rain falls through great depths of ice-cold air it freezes to solid ice spheres or " sleet " and accumulates on the ground without forming icy coatings. These differences between snow and hail and frost work and sleet and sheet ice do not help us directly to discover the original method of formation of the raindrop, though they have contributed new suggestions.

It is generally stated that the smaller particles of water come together to form the larger drops, but how this is brought about is a matter that still remains to be satisfactorily determined. It is commonly said that the fine cloud particles at the upper, outer surface of the cloud become colder by rapid radiation and therefore condense more moisture upon themselves and descend more rapidly than the smaller particles, and grow by attaching them to themselves, soon reaching the limit of size and velocity.

But although this explanation may apply to some cases, yet it seems inappropriate to many others. Large drops are known to fall from an apparently clear sky, and a sheet of cloud is often noticed, from one end of which copious rain is falling, but not from the other; or a thundercloud, black and threatening, from which apparently no rain falls until a lightning flash occurs, and then rain descends torrentially in large drops; but this does not prove that the lightning is the cause of the rain; it may be one of the effects, and probably is. Some connection between lightning, thunder, and rain apparently exists, but what, is not yet clearly made out.

Rain-making by Concussion.—The hypothesis suggested centuries ago that any loud noise, such as thunder or cannonading, or even the ringing of bells, jostled the small drops together so as to form large ones and rain, was fully disproved by the experiments made at the United States Government's expense in 1892. An appropriation for this work was made by Congress in deference to a widespread popular demand that something be done to relieve the dryness of our arid regions and our droughty summers. Several popular writers had diffused the illogical conclusion that since great battles are frequently followed by rain,[1] therefore the noise of the cannon or the clashing of swords against coats of mail had caused the formation of raindrops.

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[1] Probably because they usually begin on fair days, and rain falls one day in three at least, on the average, in any region populous enough to mobilize any considerable fighting force.

In the Government tests heavy charges of explosives, such as dynamite and rosselite, were carried aloft and even into the interior of clouds by means of kites and balloons, and exploded there, but with no resulting rain. Similar experiments were made by others, and some tried even the foolish method of the fakirs, who send small quantities of gas or vapor into the air. But the general result is that no rain has as yet been brought down from the clouds by any human agency.

Destruction of Hailstorms by Concussion.—The ringing of church bells has for ages been practiced in southern Europe as a method of preventing hail, although the foolish practice was forbidden long ago by papal decree. Of late years a form of hail cannon has been widely employed in parts of Europe for shooting vortex rings of smoke upward, under the impression that such rings would break up the ascending or gyrating currents that are supposed to make hail. But it has been abundantly shown by Professor Pernter and others that such vortex rings have no appreciable influence on the formation and path of a hailstorm.

The lightning rod of Benjamin Franklin, originally intended to protect from destruction by lightning, was afterwards assumed to protect also from the hail which accompanies thunderstorms. But the collected statistics do not confirm this assumption.

How to Determine the Size of Raindrops.—A method of determining the relative size of raindrops and an approximation to their actual diameters was devised by W. A. Bentley, of Jericho, Vermont, and applied by him during several years.[1] His method consisted in allowing a little rain to fall into a layer of flour, where each drop formed a ball of paste of definite size and weight. When the large drops fell with great velocities they broke up into smaller ones, but the sum total of the weights was the same. Bentley then allowed some measured drops to fall into the flour and from the paste balls thus formed determined the relation between the balls and the sizes of the drops and the rates of fall. Out of hundreds of measurements in northern Vermont he found that the drops of different sizes occurred about as shown in Table XXX.

It is possible that the very smallest size often escaped observation, so that the relative per cent of 17 needs to be increased. Analogous determinations made by a very different method by Defant at Innsbruck, Austria, showed that the drops whose weights were to each other as 1, 2, 4, 8,

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[1] See *Monthly Weather Review*, October, 1904.

TABLE XXX.

Measurement of Raindrop Diameters and Frequencies.

APPARENT SIZE	DIAMETER OF DROPS.		FREQUENCY OF DROPS.	
	In Inches.	In Millimeters.	Number Observed.	Per Cent of Total.
Very small	Less than 0.033	Less than 0.8	149	17
Small	0.033 to 0.055	0.8 to 1.5	288	34
Medium	0.067 to 0.125	1.6 to 3.3	254	29
Large	0.143 to 0.200	3.4 to 5.0	141	16
Very large	More than 0.200	More than 5.0	35	4
Total			867	100

were most frequent, that the weight " 3 " rarely occurred, while " 5 " and " 7 " never occurred.

The sizes of the largest possible drops have been carefully investigated by Wiesner, who concluded that natural raindrops cannot exceed a weight of 0.2 gm. and a radius of 3.6 mm., or a diameter of 7.2 mm. Similarly Ritter found that the largest drops of natural rain did not exceed 0.14 gm. in weight, or a radius of 3.3 mm., or a diameter of 6.6 mm. In ordinary showers the largest natural drops he observed were only 0.065 gm. Therefore 4 mm., or 0.16 inch, may be accepted as the radius of the largest raindrops that can occur.

Experiments on the falling of large drops show that these are continually splitting into smaller ones as they fall. A series of instantaneous flash-light photographs shows that the drops are perpetually changing in shape as they fall, and that occasionally they stretch so as to break in two. This break is simply a rending of the external layer or skin of the drop.

Temperature of Rain.—Although we often speak of cold rains and warm rains, yet this term applies more especially to the air through which the rain is falling. Measurements of the temperature of the rain water have not often been made satisfactorily, but in general it may be said that the falling raindrops, by evaporation at their surface, quickly assume a temperature closely corresponding to that of the wet-bulb thermometer in the lower atmosphere, and this is always higher than the dew point but lower than the air temperature. Four years of observations in Germany, covering 68 thunderstorms, showed that the temperature of the rain was 3° C. lower than that of the air when the storms came from the northwest, north, or northeast, but only 0.8° lower for storms coming from the south, southwest, and west. When hail fell with the rain the temperature of the water was always much higher than that of the hail. In one extreme case the temperature of the hail being 0° C., that of the rain was 2.3° and that of the air 11.4°. In general, therefore, the temperature of the rain may be taken to be always somewhat lower than that of the atmosphere.

Rainfall and its Measurement.—The quantity of rain at any station is measured by means of a rain gauge and expressed as a depth of water. The horizontal area over which we imagine this measurement to apply must depend upon our idea as to whether we are dealing with a local rain or a general rain, and this can be determined only by plotting a number of records on a weather map. A difference of 50 per cent within 5 miles or 100 per cent within 10 miles can easily occur. From a study of many gauges located within 10 miles of Berlin, Hellmann found that even in monthly totals gauges 1,500 feet apart were as likely as not to differ 5 per cent, while of course in special rains they would differ 100 per cent.

No special definition has as yet been given to what are called "local rains," and a discussion of all the rainfall data day by day for some one year would be necessary in order to define the average area covered by a local rain. As cases have occurred in which many inches of rain have fallen within a few hours at a given point, while none fell 10 miles away, it will be necessary to distinguish between cloudbursts or remarkable local rains and the ordinary cases of excessive rainfall. The data for the study of these ordinary cases are given in the tables of excessive rainfall published by many weather bureaus, and especially in the chapter on rain density or intensity in Hellmann's discussion of the rainfall of Germany.

The accuracy of rainfall measurements has not yet been determined satisfactorily because the principal source of error—namely, the action of the wind at the mouth of the gauge and in the region surrounding any two gauges—is so irregular and so variable that it has thus far been found impossible to make an accurate allowance therefor. By protecting the mouth of the gauge from injurious wind effects one may reduce the error of the catch to within 5 per cent. Methods of doing this were first recommended by Prof. Joseph Henry, in 1856, who surrounded the gauge with a collar. Professor Nipher, in 1875, surrounded the gauge with an umbelliform structure of open wirework. Börnstein and Wild protected the gauge from wind by a near-by fence. Hellmann found that gauges in the center of a depressed roof or protected by the balustrade of a roof were satisfactory. But when we attempt to compare two gauges a short distance apart we find that local wind effects exist, due to buildings and slight irregularities in the ground, so that the comparison of two protected gauges does not eliminate this source of error.

Eastman, at the Naval Observatory, Washington, D. C., placed a number of gauges in one compact bunch; and a similar experiment was tried by the Weather Bureau at an exposed point on the North Carolina coast in 1881. In both cases it was as though a gauge of several square feet aperture were divided up into a number of smaller apertures; but in both cases the action of the wind on the windward side of the bunch was very different from its action on the leeward side, so that no conclusion could be drawn as to the relative accuracy of different gauges or of the total catch. The horizontal variations of rainfall and the accuracy of the measurements are questions still requiring elucidation.

VARIATION OF RAINFALL AND OF ITS CATCH WITH ALTITUDE.—The variation of rainfall with height in the atmosphere is a subject that must be divided into three sections: first, the effect of altitude above the ground on the catch of the gauge; second, its effect on the rainfall proper; third, the influence of the lay of the land, slopes, plateaus, and mountains, on the formation of rain.

1. As to the height of the gauge above ground, there is a very rapid diminution of the catch, which is represented approximately by the formula " deficit equals 6 times the square root of h," which gives the deficit in percentages for any height in meters. This deficit is demonstrably due wholly to the action of the wind in carrying the smaller raindrops past the mouth of the gauge and allowing only those heavier drops to be caught which fall rapidly enough to pierce through the thin, swift current of air and the eddies that exist just above the mouth of the gauge. In perfect calms this error does not exist, and in strong winds with light rains it is much larger than the above rule will give. The rule is based upon the average of all European and American observations of rain, but excludes snow.

When a gauge is established in a forest or has other protection, its records increase; when the protection is removed the recorded rainfall diminishes. Gauges that have been maintained for many years in the same spot are liable to have their records appreciablv altered by slight changes in their surroundings. The only practicable way of attaining accurate knowledge of the rainfall of any locality is to increase as far as possible the number of gauges, the variety of localities, and the perfection of the protection.

2. As to the effect of the altitude above ground on the rainfall proper, nothing remains to be said if we assume that all the variations in catch

are due to the wind. It has been supposed that raindrops falling through dry air would evaporate slowly, so that rain catch should increase with altitude, and *vice versa* when they fall through foggy air; but neither of these influences is appreciable for such elevations as it is practicable to attain with gauges in free air. It is only rarely that we see a few streaks of falling rain or snow disappear before they reach the ground, and it is quite possible that the disappearance of rain is in part due to the breaking up of large drops into small ones.

A special snow gauge was established on the summit of Pike's Peak by Professor Marvin. It was a tube about 30 feet high, with a wind vane at the top that kept the mouth turned toward the wind. It therefore caught all the snow contained in a stream of air that entered the mouth and, descending, passed out at the lower, open end of the tube. It therefore measured the sum total of the snow blowing past the summit of the peak rather than that which rested on the ground, which latter was a very small quantity. He thus obtained an idea of the condensed moisture in a layer of air 14,500 feet above sea level, on which item several interesting conclusions may be based.

3. The orography of a region determines largely the extent to which masses of air will be pushed by the wind upward to the cloud level. In the case of the long, gentle rise without any sudden change in the temperature of the air, the latter would eventually arrive at a region where cloud will form and rain will fall from it at a maximum rate; and as it passes beyond, higher up, the rate of fall will diminish. The law connecting the formation of rain with this gradual rise of the land was first ascertained from observation, by S. A. Hill, in studying the rainfall of India; the theoretical study of the subject, based on the laws of thermodynamics and hydrodynamics, was first carried out by Pockels,[1] from whose paper it would seem that there may in some cases be several successive regions of maxima and minima of rainfall. In general, however, our sloping plains are not long enough nor broad enough to include more than one such maximum. In the case of the wind blowing against the broad side of a long mountain ridge, the region of heavy rainfall on the windward side sometimes extends up to the very crest and is paralleled by a similar region very far to leeward where the immense atmospheric billows extend high enough to form another belt of cloud and rain.

When a mountain range or plateau extends above the region of maximum rainfall it is liable to attain the altitude of diminished rainfall or possibly of none at all. As the altitude of maximum rainfall varies with the condition of the atmosphere and therefore with the season of the year, most of the elevated rainfall stations show corresponding fluctuations in rainfall, leading to the study of local geographic distribution of rain. A special study of this kind by Supan has served to explain the annual variations on the elevated regions of Europe, which are sometimes directly opposite to the variations in the lowlands. In fact, in several cases Supan finds a secondary maximum of rainfall located above the primary.

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[1] See *Monthly Weather Review*, 1901, p. 152.

Diurnal Variation in Rainfall.—As to the diurnal variation in rainfall, a large number of stations on continental coasts have their maximum rainfall in the early morning or late night hours, and their minimum in the afternoon. Another class of stations has a minimum between 8 A.M. and noon; while still another has the maximum in the early hours after noon. The most common case is that in which the minimum rainfall occurs during those hours of the day when the temperature is rising most rapidly —say from 8 A.M. to noon—followed, of course, by heavy rains at some later hour. These rules, however, are liable to be completely reversed by the change from summer to winter. In so far as local rains depend upon the arrival of local thunderstorms starting from some distant mountain region, each locality has its special hour at which to expect the rain.

Within the tropics the annual march of the sun north and south of the equator brings about a complete double change in the diurnal maximum rainfall; thus at Batavia, in January–February, the maximum is between 4 and 6 A.M., but in October–November it is between 4 and 6 P.M.

Annual Variation in Rainfall.—As to the annual period in rainfall, the most convenient method of comparing a large variety of climates is to express the monthly quantities as percentages of the annual total. Of course some way must be found to allow for the differences in the lengths of the months, and the method of Angot is recommended, but that of Quetelet and Kreil is equally good, though more laborious. The annual periodicity leads us to the study of the differences between continental, coastal, and oceanic locations, and that between monsoon regions and tropical regions on one hand, which have but one annual variation, and on the other hand the equatorial zone, which has two annual variations.

The distribution of the annual quantity of rain over the whole globe cannot yet be studied satisfactorily because of our ignorance of the rainfall of the oceans. The map given by Supan for America, Asia, the Atlantic and Indian oceans, represents the best of our knowledge at the present time; according to which the mean annual rainfall for the region 10° north of the equator and across the Atlantic Ocean is 145 inches, while for the land surfaces of the whole globe on the same zone the rainfall is only 83 inches. From this zone the quantity diminishes as we go northward and southward, and would scarcely average 39 inches at latitude 60° north or south.

Gauge for Recording Evaporation and Rain.—This instrument (Fig. 78) was designed by Prof. C. F. Marvin for the use of the Weather Bureau in its observations of the evaporation at the Salton Sea and elsewhere. It consists of a large tank nearly filled with water, which is maintained at a perfectly constant level by the aid of a float riding upon the surface of the water in a still well, or small auxiliary tank, communicating with the large tank by a siphon or other connection. Whenever as much as 0.05 mm. of water has evaporated from the pan, the fall of the float occasioned thereby operates, electrically, to open a valve and admit

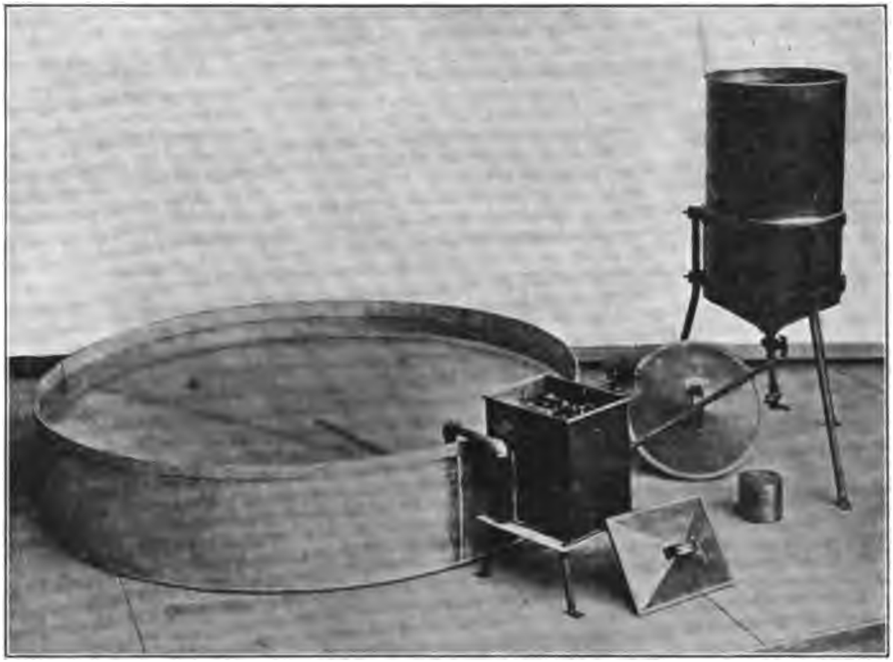

Fig. 78.—Evaporation Recorder (Marvin).

just enough water to raise the level to the normal point. The quantity of water admitted is accurately measured by the use of a tipping-bucket, similar to those employed in recording rainfall. Each tip of the bucket is recorded electrically on a register that may be located some distance away. The supply of water is drawn from a closed vessel, so arranged as to show the gross amount of water delivered to the tipping-bucket, thus affording a check on the record.

In the complete design a second electrical valve and tipping-bucket draws off, measures, and records any excess of water above the normal level caused by rainfall. This part of the apparatus was not required at the Salton Sea, and is not shown in the illustration.

BIBLIOGRAPHY

MARVIN, C. F., "Measurement of Precipitation," 2d ed., Washington, 1903. (United States Weather Bureau, *Circular E,* Instrument Division.)

Many valuable papers on rainfall and rainfall measurement have appeared in the annual volumes of *British Rainfall,* London, 1860 to date. See list in the 1900 volume, pp. 42–45.

IMPORTANT COLLECTIONS OF RAINFALL STATISTICS

SUPAN, ALEXANDER, "Die Verteilung des Niederschlags auf der festen Erdoberfläche," Gotha, 1898. (Petermanns Mitteilungen, Ergänzungsheft No. 124.) The tables herein are the chief collection of rainfall normals for the world at large, exclusive of Europe.

HELLMANN, G., "Die Niederschläge in den norddeutschen Stromgebieten," Berlin, 1906, 3 vols. A vast compilation of collected data and normals of precipitation for the greater part of Germany and extensive areas of contiguous countries. Vol. I contains elaborate analysis of special features of the precipitation; a bibliography (pp. 31–36); and a detailed rainfall chart of Germany.

WILD, H., "Die Regen-Verhältnisse des russischen Reiches," St. Petersburg, 1887. With atlas.

ELIOT, SIR JOHN, "The Rainfall of India," Calcutta, 1902. (Indian meteorological memoirs, v. 14.)

GREAT BRITAIN, METEOROLOGICAL OFFICE, "Rainfall Tables of the British Islands, 1866–1890," London, 1897. (Official, No. 114.)

HENRY, ALFRED J., "Rainfall of the United States, with Annual, Seasonal, and Other Charts," Washington, 1897. (United States Weather Bureau, *Bulletin D.*) Also published as part 7, United States Weather Bureau, *Report of the Chief*, 1896–97, Washington, 1897.

NOTABLE WORKS ON SPECIAL FORMS OF PRECIPITATION

RUSSELL, ROLLO, "On Hail," London, 1893.

BENTLEY, WILSON A., "Studies among the Snow Crystals," Washington, United States Weather Bureau, *Monthly Weather Review*, 1902. Illustrated with 255 photomicrographs of snow crystals.

CHAPTER XIII

FORECASTING THE WEATHER AND STORMS

To one who will study this chapter and carefully follow the charts as they successively illustrate the text, the daily weather map will become an object of pleasure and profit. Sometimes the problems presented by the map are so simple that one possessed of the most elementary knowledge of its construction can accurately forecast the character of the coming weather; and again, the most expert forecaster is unable to clearly foresee the impending changes.

Weather maps differ as much as do the members of the human family; no two are precisely alike, although they may be similar in their fundamental characteristics. Some are so radically dissimilar from others that it requires but a glance to learn that similar weather cannot follow both. While but less than a century ago we knew not whence the winds came nor whither they went, we are now able, through the aid of daily meteorological observations and the telegraph that joins our places of observation by an electric touch, to trace out the harmonious operations of many physical laws that previously were unknown, and that determine the goings and the comings of the winds, and the sequence in which weather changes occur; but in weather forecasting it will never be possible to attain the accuracy acquired by astronomers in predicting the date of an eclipse or the occurrence of other celestial events.

The Beginning of the American Weather Service.—Although American scientists were pioneers in discovering the progressive character of storms and in determining the practicability of forecasting the weather, the United States was the fourth country to give legal autonomy to a weather service. Only an international institution, embracing all the countries of Europe, could equal the service of the United States in extent of the area covered. Furthermore, forecasts for the countries of western Europe can never cover the time in advance or attain the accuracy of those made for the region east of the Rocky Mountains on the American continent, because of the ocean that lies to the west of these countries in Europe, from which it will always be difficult to secure observations. To be sure, wireless telegraphy may partly relieve the situation, but irregular observations from moving vessels cannot completely take the place of stable land stations.

At the time of the beginning of the U. S. weather service, in 1870, and for some years thereafter, the forecasts and storm warnings were looked upon as experiments of doubtful utility. We had not had the opportunity to train a corps of expert forecasters, such as now form a considerable part of the staff of the Chief of the Weather Bureau, and from which he himself was graduated. After a time mariners began to note that in the majority of cases storm warnings were followed by dangerous winds. With experience the warnings became still more accurate, until now no port, however small, is without its storm-warning tower, and no mariner sails the seas who does not consult the signals, and no shipper of perishable commodities runs his business a day in the winter without being in touch with the source of cold-wave warnings, and no large grower of fruits or vegetables is content to be excluded from the receipt of the frost forecasts.

Redfield, Espy, Henry, Loomis, Maury, Abbe, and Lapham are the Americans to whom the world owes most for the founding of meteorological science and for the demonstration of the feasibility of the weather forecasts.

How the Daily Weather Chart is Made.—It is essential to a comprehension of the problems involved in the making of forecasts that one gain a knowledge of the methods of gathering meteorological observations and making weather reports. Each morning at 8 o'clock—75th meridian time—which, by the way, is about 7 o'clock at Chicago, 6 o'clock at Denver, and 5 o'clock at San Francisco—the observers at about 200 stations scattered throughout the United States and the West Indies take their observations, and, with the aid of carefully tested instruments, note the pressure of the air, the temperature, the humidity, the rainfall or snowfall, and the cloudiness. During the next 30 to 40 minutes these observations are speeding to their destinations, each station contributing its own observations, and important stations receiving in return such observations from other stations as they may require for the making of forecasts.

Before examining the accompanying charts it may be well to glance at the central office in Washington, while the observations are coming in, so as to get an idea of how the charts are made for the study of the forecast official. As fast as the reports come from the wires they are passed to the Forecast Division, where a force of clerks is engaged in making representations of the geographical distribution of the different meteorological elements. On blank charts of the United States each clerk copies that part of each station's report needed in the construction of his particular chart. One clerk constructs a chart showing the change in temperature during the preceding twenty-four hours. Broad red lines separate the colder from the warmer regions, and narrow red lines inclose areas showing changes in temperature of more than 10°. The narrow lines generally run in oval or circular form, indicating (as has been shown) that atmospheric disturbances operate in the form of great progressive eddies.

A second clerk constructs a chart showing the change that has occurred in the barometer during the past twenty-four hours. As in the construction of the temperature chart, broad lines of red separate the regions of rising barometer from those of falling barometer. Narrow lines inclose the areas over which the change in barometer has been greater than one tenth of an inch; inside of these lines other lines inclose the areas where the fall has been two tenths, and so on.

Here, for instance, throughout a great expanse of territory, all the barometers are rising—that is to say, in this region the air is cooling and contracting, and therefore allowing that of adjacent warmer sections to flow in at the higher levels. Thus the total quantity of air resting on any given area at the ground is increased, and hence the barometers stand correspondingly higher. Over another considerable area the barometers are falling as a result of the air above them flowing away to cooler regions.

This chart indicates whether or not the storm centers are increasing or decreasing in intensity, and, what is of more importance, it gives in a great measure the first indication of the formation of storms.

A third clerk constructs two charts, one showing the humidity of the air and the other the cloud areas, with the kind, amount, and direction of the clouds at each station. It is often interesting to observe at a station on the cloud chart high cirrus clouds composed of minute ice spiculæ moving from one direction, lower cumulo-stratus composed of condensed water vapor moving from another direction, and the wind at the surface of the earth blowing from a third point of the compass. Such erratic movements of the air strata are only observed shortly before or during storms.

A fourth clerk constructs a chart called the general weather chart, showing for each station the air temperature and pressure, the velocity and direction of the wind, the rain- or snowfall since the last report, and the amount of cloudiness. The readings of the barometer on this chart are reduced to sea level, so that the variations in pressure due to local altitudes may not mask and obscure those due to storm formation. Then lines, called isobars, are drawn through places having the same pressure. By drawing isobars for each difference in pressure of one tenth of an inch the high- and the low-pressure areas are soon inclosed in their proper circles. The word " high " is written at the center of the region of greatest air pressure and the word " low " at the center of the area of least pressure. Under the influence of gravity the air at any point presses equally in all directions, thus causing it to flow from a region of greater pressure toward one of less. The velocity with which the wind moves from the high toward the low will depend largely on the difference in air pressure. To better illustrate: If the barometer read 29.5 at Chicago, Ill., and 30.5 at Bismarck, North Dakota, the difference of 1 inch in pressure would cause the air to move from Bismarck toward Chicago so rapidly that after allowing for the resistance of the ground there would remain a high wind at the surface of the earth, and Lake Michigan would experience a severe " northwester."

Cyclonic Storms.—Chart No. 19 shows a winter storm (cyclone) central in Iowa at 8 A.M., December 15, 1893. The word " low " marks the storm center. It is the one place in all the United States where the barometer reading is the lowest. The heavy black lines, oval and nearly concentric about the low, show the gradation of air pressure as it increases quite uniformly in all directions from the storm center outward.

The arrows fly with the wind, and, as will be seen, are almost without exception moving indirectly toward the low or storm center, clearly demonstrating the effect of gravity in causing the air to flow from the several regions marked high, where the air is abnormally heavy, toward the low, where the air is lighter. As the velocity of water flowing down an inclined plane depends both on the slope of the plane and on the roughness of its surface, so the velocity of the wind as it blows along the surface of the earth toward the storm center depends on the amount of the depression of the barometer at the center and the resistance offered by surfaces of varying degrees of roughness. The small figures placed at the ends of the arrows indicate wind velocities of 6 miles per hour and more. At Chicago, where the wind is blowing at the rate of 40 miles per hour, the anemometer is 270 feet high, while at St. Paul, where the instrument is so low as to be in the stratum whose velocity is restricted by the resistance encountered in flowing over forests to the northward, the rate is not great enough to be marked by a figure. At Chicago and Davenport the wind is blowing against the pressure gradient, away from the low. This is due to the fact that it has flowed swiftly from the south and gained such momentum that it rushes by the storm center before the gradient on the north of the center can overcome its movement and turn it.

Now picture the fact that all the air inside the isobar marked 30.2, as it moves spirally inward, is rotating about the low in a direction contrary to the movement of the hands of a watch, and you have a very fair conception of an immense atmospheric eddy, or cyclone.

Storms may be likened to great eddies or vortices in the air that are carried along by the general easterly movement of the atmosphere in the middle latitudes of both hemispheres and by the westerly movement of the general circulation in the tropics. But, as previously stated, they are not deep eddies. The low shown on Chart 19 marks the center of an atmospheric circulation of vast horizontal extent as compared with its thickness or extension in a vertical direction; thus a storm condition extends from Washington to Denver in a horizontal direction, and yet extends upward but 3 or 4 miles. The whole disk of whirling air is a cyclone. It is often called a " low " or a " low pressure." The weather experienced from day to day depends wholly on the movement of cyclones and anticyclones.

One should gain a clear understanding of the difference between the movements of the air in the cyclone and the movement of the cyclone itself, or its translation from place to place; how the wind must blow *into the front* of the storm in a direction partly or wholly contrary to the movements of the storm itself and *into the rear* of the storm as it passes away; how the wind increases in velocity as it gyrates spirally about the center and approaches nearer and nearer the region where it ascends; how the higher layers of air move away from the center and cause an accumulation of air about the outer periphery of the storm, which in turn presses downward and impels the surface air inward. This whole complex *system of motions* moves forward.

The black round disk indicates that the weather is cloudy at the moment of the observation, and the open disk clear sky. S. and R. stand for snow and rain. The large figures in the four quarters of the cyclone show the average temperature of each quadrant. The greatest difference is between the southeast and northwest sections. This is due in part to the fact that in the southeast quadrant the air is drawn northward from warmer latitudes, and in the northwest quadrant the air is drawn southward from colder latitudes.

Chart 20, constructed from observations taken twelve hours later, shows that the storm or cyclonic center, as indicated by the word " low," has moved from central Iowa since 8 A.M. and is now, at 8 P.M., central over the southern point of Lake Michigan. The shaded areas show that precipitation has occurred during the past twelve hours in nearly the entire region covered by the cyclone. Unfortunately for the art of weather forecasting, precipitation does not always show that relation to the configuration of the isobars that temperature, wind velocity, and wind direction do.

Note that none has fallen in the southern portion of Ohio, in northwest Missouri, and in West Virginia and eastern Kentucky, although they are near the storm center, while a fall has occurred in New England, quite remote from the center of barometric depression. These facts illustrate how a forecast of rain or snow may fail for a portion of a state or for a whole state, even though the storm pass over the state and the wind and temperature change precisely as predicted. However, all the places mentioned as failing to receive precipitation were showered upon during the further progress of the storm, except northwest Missouri, as will be seen by referring to Chart 21 of the following morning. The cyclone has continued its course toward the northeast, and has brought the rain area eastward to include nearly the whole Atlantic coast region. The weather has cleared on the west side of the storm.

Charts 20 and 21 contain red lines, which, like the dark shading, do not appear on Chart 19, which was purposely left clear of these symbols, so that the movement of wind in accordance with pressure gradients could be the better shown. These red lines connect places having the same temperature. Note how, on both charts, they trend from the Atlantic coast northwestward into the southeast quarter of the cyclone, and where they leave the storm center how precipitately they drop away toward the southwest. A cause can be easily found for this by examining the direction of the arrows. In the first case the isothermals are being pushed northward by southerly winds, and in the other forced southward by winds from the northwest. As the cyclone proceeds eastward the regions now under the influence of warm southerly winds will be, in less than twenty-four hours, on the west side of the storm, and cold northwest winds will sweep over them.

The line of arrows leading from western Wyoming to the center of the storm on Chart 21 shows the place where the cyclonic circulation of wind began that constitutes the storm and the course pursued by the storm center. The small circles surrounding crosses mark the places where the storm was central at each twelve-hour interval. The figure above the circle indicates the date, and the letter below evening or morning.

As previously explained, the large figures give the average temperature for each of the four quarters of the storm within a radius of 500 miles from the center. The same information may be gathered from the isotherms, but cannot be so strikingly presented. Now, remembering that the air ascends as it spirally moves around the center, one may understand how the cold air of the northwest quarter is mingled with the warm air of the southeast portion.

The two quarters are represented—one by 13° and the other by 47°. The mixing of such cold and such warm masses of air, and, more important, the cold due to expansion as the mixture rises, is a fruitful cause of precipitation. We see that rain has fallen in the Gulf States, probably only as the result of cold northwest winds underrunning and lifting up the warm air of the south. Precipitation may also occur as the result of other processes not yet understood.

Anticyclonic Storms.—Attention is now directed to the *anticyclone* or high-pressure area shown on these three charts as resting over the Rocky Mountain plateau. Here all the functions of the cyclone are reversed; hence the name anticyclone. The air has a downward component of motion at and for a considerable distance from the center, instead of an upward component; the winds blow spirally outward from the interior, instead of inward, and rotate with the hands of the watch,[1] and the air is mostly clear, cool, and dry, instead of cloudy, warm, and humid. The center of this high moved but little during the two twelve-hour periods, but its area expanded eastward as the low advanced, and if the chart of December 17th, 8 P.M., were shown the high pressure would be seen to cover with clear, cool weather the region now embraced within the limits of the low pressure.

These are winter conditions that are being described. The storms are general, not local, as is more often the case in summer, when the highs and the lows exhibit small differences of pressure, move slowly, and seldom embrace large areas. The summer type of local storms gradually merges into general storms as the heat of summer wanes, the first general rain-storms usually occurring during the latter part of September. This has given rise to the erroneous idea of an " equinoctial storm."

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[1] The direction of rotation of cyclones and anticyclones is reversed in the southern hemisphere.

Hot Waves.—In summer there come periods of stagnation in the drift of the highs and the lows. At such times, if a high sluggishly rests over the South Atlantic Ocean between Bermuda and the coast of the United States and a low over the northern Rocky Mountain region, there will result what is popularly known as a warm wave, for the air will slowly and steadily flow from the southeast, where the pressure is greater, toward the northwest, where the pressure is less, and, receiving constant accretions of heat from the hot, radiating surface of the earth, without any cyclones to mix the upper and lower strata, will finally become abnormally heated. This superheated condition of the lower stratum continues until the high over the ocean dies out or drifts away to the east and the low-pressure area in the northwest begins to gyrate as a cyclone and moves eastward, mixing in its course strata of unequal temperatures and causing cool thundershowers.

Cold Waves.—Chart 22 shows the beginning of a cold wave in the northwest on the morning of January 7, 1886. Observe that the heavy, black isobar passing through Montana is marked 30.9, while the isobar curving through southern Texas is marked 29.8, a difference of 1.1 inches in the air pressure between Montana and Texas. The red isothermal line in Montana is marked 30° below zero, while the isotherm on the Texas coast indicates a temperature of 50°. From the distribution of air pressure shown by this chart, and the known drift of the upper air into which the high and the low penetrated, the forecaster anticipated that the cold air of the northwestern states would be forced southward to the Gulf and eastward to the Atlantic Ocean, or, more accurately speaking, that the conditions causing the cold in the northwest would drift southward and eastward. He therefore issued the proper warning to the threatened districts.

Now turn to Chart 23 of the following morning, and it will be seen that the cold wave has covered the entire Mississippi valley. The 10° isothermal line has been forced southward almost to Galveston, where the temperature the preceding morning was 50°.

The low shown on the preceding chart as being central in southern Texas as an incipient storm has moved northeastward to Alabama, as might be expected by one who remembers what was said in Chapter IX about the general eastward drift of the atmosphere in middle latitudes, and now appears as a fully developed storm.

The difference in pressure between the central isobar of the low and the central isobar of the high is now 1.4 inches. The low is lower and the high is higher—conditions that augur ill for the coast line toward which the low is moving. Next look at the arrows at the coast stations from Key West, Florida, to Eastport, Maine; each is found to have a short bar at one end, which indicates that every port, large and small, between these two places is flying a danger signal, and that every promontory or island along this vast stretch of seashore will exhibit the warning lights of the Weather Bureau as soon as night comes.

Forty years ago mariners depended on their own weather lore to warn them of coming storms; then, although the number of ships plying the oceans was much less than it is now, every severe storm that reached navigable waters left death and destruction in its wake, and for days afterwards the dead were cast up by the subsiding seas and the shores were lined with wreckage that represented a loss of many millions of dollars. Happily this is not now the case; the great mass of shipping takes warning and rides safely at anchor in convenient harbors.

The large figures in the four quarters of the low again strikingly illustrate how great may be the difference in temperature, under cyclonic influence, between regions separated by but short distances.

It is certain that as the low or cyclonic whirl moves toward the northeast, along the track usually followed by storms in this locality, the cold of the northwest quadrant, by the action of the horizontally whirling disk of air that constitutes the low, will be driven southeastward toward Florida, lowering the temperature in the orange groves to below the freezing point.

Chart 24 shows that the center of the cyclone has moved during the preceding twenty-four hours northeast to the coast of New Jersey, with greatly increased energy, the barometer at the center showing the abnormally low reading of 28.7 inches. Cold northwest winds, as shown by the arrows, are now blowing systematically from the high-pressure area of the northwestern states southeast to Florida and the South Atlantic coast. The red isotherm of 30° passes through the northern part of Florida, where, on the day before, the temperature was over 50°. The cyclonic gyration of this storm extends 1,000 miles inland and to an equal distance out to sea. Heavy snow or rain has fallen throughout the area under its influence, seriously impeding railroad travel, and a gale of hurricane force has prevailed on the coast; but when, on the day preceding, the storm was central in Alabama all these conditions were foreseen and the necessary warnings issued.

Chart 25 shows the conditions twenty-four hours later. The storm center, as shown by the line of arrows, has been three days in passing from southern Texas to the mouth of the St. Lawrence. The temperature has fallen still lower on the Atlantic coast and in Florida as the result of uninterrupted northwest winds, and no material rise in temperature can occur until the high pressure of the northwest is replaced by a low pressure, and convectional currents are drawn toward the northwest instead of being forced southward from that region.

When the charts indicate the formation of a large volume of dense, cold air in the northwest, as shown by the barometer readings, the skilled forecaster is on the alert. He calls for special observations every few hours from the stations within and directly in advance of the cold area, and as soon as he becomes convinced that the cold wave will sweep across the country, with its attendant damage to property, destruction to animal life, and discomfort to humanity, the well-arranged system of disseminating warnings is brought into action, and by telegraph, telephone, flags, bulletins, maps, and other agencies the people in every city, town, and hamlet, and even in farming settlements, are notified of the advancing cold twelve, twenty-four, or even thirty-six hours before it reaches them; and it is safe to say that $10,000,000 is a low estimate to make of the value of the perishable property that is protected in the United States as the result of the warnings that are distributed by the Government in advance of the coming of only one of several severe cold waves that occur each winter.

In the late spring and early fall the highs, or anticyclones, while possessing less energy than in the winter, under favorable conditions lead to such unseasonably low temperatures as to cause injurious or destructive frosts, the frosts being due in part to the cool air of the high, but especially to the clearness of the air, which allows a free escape of heat from the earth by radiation at night. As in the case of cold waves, warnings are widely distributed in advance of the high that may cause frosts, with great profit to the growers of tender fruits and vegetables.

In a general way the degree of cold in a cold wave, or rather the departure of the temperature from the normal of the season, will be proportional to the height of the barometer; a necessary concomitant of a cold wave is an area of low pressure immediately in advance of the high pressure, the upward movement in one increasing the downward motion of the other; the greater the difference in the barometer between the two the greater the velocity with which the air will gyrate about and into the low, and the greater the downward and outward movement of the air in the high, and the more intense the cold. It therefore follows that a high that is not preceded by an active low will have a less degree of cold for a given pressure, and that the extent and intensity of cold waves depend considerably on the form and the characteristics of the preceding low and its location; if north of the center of the United States the cold that follows will not reach the Gulf States in severe form, if at all; but if a low of considerable energy forms in the region of Texas and moves northeastward to the Atlantic coast, as nearly all lows do that originate in this region, and a high of equal intensity develops at the same time over the northern plateau of the Rocky Mountains, the latter will be drawn far to the south, as the former moves out of the way toward the east, and cold northwest winds, driven by the high and attracted by the low, flow into the Gulf of Mexico itself, even reaching the city of Mexico and the islands of the West Indies.

No Cold Waves from the Pacific.—It would be impossible for cold waves to come upon the Pacific coast states with the highs that drift in from the ocean, because of the warming effect of the water upon the air up to considerable elevations; but frosts and cold waves visit the interior valleys of California and other coast states and reach almost to the ocean's edge. They are due to highs that move southward and then eastward along the plateau. The highs may be moving eastward very slowly, but the diameter of the areas covered by them may increase so rapidly that some cold air is pushed over the mountain tops and flows from the northeast into the interior valleys of the coast states.

Thermal Limits of Cold Waves.—The U. S. Weather Bureau has adopted certain arbitrary thermal limits to determine what constitutes a cold wave. Both the extent of the fall of temperature and the degree of cold that must be reached vary for season and place. For example, in December, January, and February a cold wave in the northern Rocky Mountain region occurs when the temperature falls 20° in twenty-four hours and reaches a minimum of zero or lower; in Tennessee a fall of 20° and to 20° or lower is required, while along the Gulf coast a fall of but 16° and to 32° constitutes a cold wave. The fall in temperature is reckoned from any given hour of one day to the same hour of the next day or from the minimum of one day to the minimum of the next.

Geographic Origin of Cold Waves.—The area and the intensity of cold waves depend largely upon the sizes of continents and their distance from the tropics. The interior of North America and of Siberia have geographic conditions that cause the most severe cold waves of any parts of the world. If the elevation of the Rocky Mountain plateau in North America were one half of what it is and if the mountain chains were leveled away, or even trended to the east and west instead of north and south, the vaporous atmosphere of the Pacific, which decreases in density rapidly with elevation, would flow far into the interior of the continent, and by absorbing the heat of the sun during the day and restricting radiation from the earth at night markedly decrease the severity of cold waves and other changes in temperature. Hence it is seen that the heights of mountain systems and their trend relative to large bodies of water and to the prevailing direction of winds are important factors in the causing of cold waves.

Dynamic Heating, and Cooling by Radiation, in an Anticyclone.—As stated before, the air has a downward movement in the anticyclone, which may be so feeble as to cause only a slight change in temperature at the earth, or it may be active enough to lower the temperature down to the frost line in spring or fall, or have such energy as to cause a cold wave in winter. In the latter case the air possesses such intense cold at the elevation from which it is drawn and radiation is so free through its cloudless layers that, nothwithstanding the fact that it gains heat by compression at the rate of about 1° for each 200 feet of descent, it is still far below the normal temperature of the surface air when it reaches the earth. Its initial temperature is so low that it can contain only a small portion of water vapor; it therefore evaporates all fog or cloud as it gains in temperature during its fall, and by flowing away laterally along the earth it drives away the more humid air of the lower strata. The downward motion thus introduces conditions of clearness and deficiency of water vapor that promote free radiation and the loss of much of the heat dynamically gained as well as that given off by the earth to the air. It therefore seems that departures from the normal temperature of a time and place are the result of *the motions of the air* below the height of 10 miles.

SANITARY FEATURES OF COLD WAVES.—Few people realize that the cold wave has an important therapeutic value. It scatters and diffuses the carbonic-acid gas exhaled by animal life and the fetid gas emanating from decaying organic matter. Its dense air not only gives more oxygen with each inspiration of the lungs, but the high electrification that always accompanies it invigorates man and all other animal life.

Hurricanes.—Most of the storms that gain such a velocity of gyration as to constitute hurricanes originate in the tropics and move northwestward to latitudes from 26° to 32°, where they recurve and move toward the northeast. These are the most severe of all the storms that visit the North

American continent. The West Indies and the Philippines are the regions wherein these forceful storms originate in the greatest numbers and the commerce of all nations has largely profited by the spirit that has prompted the United States to establish, since 1898, a complete system of cable-reporting meteorological stations in both of these sections, which enables a central station to keep mariners advised of danger.

At times hurricanes remain several days in the Gulf of Mexico or off our South Atlantic coast, and the only indication we have of their proximity is a strong suction drawing the air briskly over some of our coast stations toward the center of the storm. Again, a heavy ocean swell may be caused by the friction of the rapidly gyrating air on the surface of the water, and when the hurricane has a slow progressive movement, as it usually has south of latitude 30°, this swell may be propagated outward from the center of the storm faster than the storm is moving and reach the coast several hours before either the barometer or the wind movement gives indication of the coming storm.

The tracks of West Indian hurricanes are usually in the form of parabolas. These storms come from the southeast, but on reaching the latitude of our Gulf coast they recurve to the northeast unless deflected by highs lying in their course.

Chart 26 shows a West Indian hurricane just making its advent into Florida. The effect of the storm is felt as far north as Wilmington, where the wind is being drawn from the northeast at the rate of 24 miles per hour, and danger warnings, as indicated by the bars on the arrows, are being displayed as far north as Norfolk, both from the regular observation stations of the Weather Bureau and from warning towers erected at numerous other harbors of the South Atlantic coast. The winds at Savannah and Jacksonville are moving from the northeast and north, respectively, at 20 miles per hour, which is 4 miles less than at Wilmington, farther away from the storm center. This apparent inconsistency may be due to the low and restricted exposure of the instruments at the nearer stations, but not necessarily so, as the winds never blow into or around a storm at velocities that are evenly and consistently in accord with the pressure gradients, but rather in the form of rising and falling gusts, and the observations at the three places were taken at exactly the same moment.

Observe that there are no warnings flying at Key West; this is because the storm center is moving away, and the wind therefore cannot reach any higher velocity than it now has, but must decrease.

In studying the winds about this storm center, or rather about such part of it as projects over the land, it will be seen that it is possible for storms to progress against the surface wind. In thunderstorms this rule does not hold. They cover but an infinitesimal area in comparison with cyclones, and there is a horizontal rolling of the atmosphere, caused by cold and heavy air from above breaking through into lighter superheated strata next the earth. This rolling motion throws forward the cool air in the direction in which the cloud is moving.

Chart 27 shows a slight aberration in the northeast course of the storm which places the center inland, so that the whole cyclone can be charted. From eastern Florida the usual course of storms is northeast over the ocean instead of up through Georgia and the Carolinas. The apparent reason for this departure is that the high over New England and the contiguous ocean has a tendency to crowd the storm inland and cause it to seek the route of least resistance, and the low over the lake region attracts it.

The storm has been destructive to marine property, the wind having reached 72 miles per hour at Savannah and 48 miles at Jacksonville, and warnings are now displayed at all ports northward to New England, as the hurricane will move northward between the two highs along the lines of least pressure. Chart 28 shows that it traveled from northern Georgia to central New York during the next twenty-four hours. The storm center passing northward over the land instead of the water, the hurricane winds on the water were onshore—a condition that strewed the coast with the wreckage of many vessels that were unable to see the warning signals in time to seek harbors of safety. It is pertinent to ask the student of weather forecasting what would have been the direction of the wind and its effect on the coast line if the storm had followed the usual course and passed northeastward with its center over the water instead of over the land. The reader should be able to answer: The winds would have been from the west and much less harmful to mariners, because the surface water would have been driven seaward instead of being banked up in boisterous billows upon the shore, and ships would have scudded out to ocean before the gale instead of being broken up on the reefs.

West Indian hurricanes are cyclonic in character, but on account of the fact that the diameter of the whirling eddy is much less and the velocity of rotation much greater than in the average cyclone, it is customary to designate them as hurricanes. In other words, the hurricane is a cyclone of small area, but of powerful vortical action, and consequently of great destructive force.

Chart 29 shows the track of the Galveston storm. The spirals are not true pictures of the storm; neither do they represent pressure lines, as other charts have done. They are used to illustrate more clearly than can be done in any other way the eddylike motion of a cyclone and at the same time give the location of the hurricane on various dates.

In explaining the hurricane of August 27, 1903 (Chart 26) it was stated that the storm was deflected a little from its normal course by an anticyclone that rested over the ocean. A similar distribution of air pressure occurred on September 6, 1900, when what we will call the Galveston hurricane was central over Florida, except that the anticyclone covered the whole region from the Mississippi River eastward to Bermuda and southward to the Gulf. The storm was therefore forced to travel westward around the high to the Texas coast before it could turn to the northeast. It was first detected in the Caribbean Sea. The velocity of translation of the rotating storm was at the rate of only about 8 miles an hour. It increased its speed between Florida and the Texas coast to about 12 miles. It did not gyrate with sufficient velocity to become destructive until after it passed into the Gulf. Then its rotary movement became so rapid that great swells were propagated outward in advance of the storm, some of which reached Galveston sixteen hours before the hurricane. As the storm passed over the latter city the anemometer registered 100 miles per hour and then broke into pieces. This was probably nearly the highest velocity reached, as it occurred at about the time of lowest barometer. which was 28.48 inches. As the storm moved toward the Lakes its rate of translation increased to about 60 miles per hour, but its destructive force was much less on the land than on the water, although it produced wind velocities of over 70 miles at several Lake stations, which, by the way, were amply warned of the coming of the storm, as were all Gulf ports.

Frequency of Hurricanes.—Between July and October, inclusive, there are annually about ten tropical storms that touch some portion of the Atlantic or Gulf coasts. On an average, less than one per annum is severely destructive. Most of them are of such a nature that if timely warnings be issued, as they usually are, little loss of life or property occurs.

As to the frequency with which these storms visit the Gulf, it may be said that the late Increase A. Lapham, of Wisconsin, carefully prepared a list of severe storms, more than thirty-five years ago, to be used by him as one of the arguments for a government weather service. He showed that from 1800 to 1870 ten hurricanes reached some portion of the Gulf coast with a force so marked as to leave authentic records in the local annals of the region. This is an average of one in each seven years. This average has been maintained since 1870; but no other storm has left such an appalling record as the one of September 8, 1900, known as the Galveston hurricane.

Geographic Conditions Favorable to Hurricanes.—It is a meteorological coincidence that the West Indies bear the same storm relation to the United States that the Philippines do to China and Japan. With the new possessions of the United States in the Orient it has been possible to establish a storm-warning service that is as valuable to the commerce plying the waters contiguous to the China coast as the service recently organized in the West Indies is to our southern seas.

The hurricanes that occur in the Philippine Islands are called *typhoons*. Like the West Indian storms, they occur mainly during four months of the year—the middle summer and early fall. The late Father Viñes, S.J., a scientist who gave much study to tropical storms, says it must be admitted that cyclones do not form at *any* place within the tropical zones, but that they single out for their formation definite regions within those zones. These regions are usually on the southwest periphery of some of the great permanent ocean anticyclones or great centers of action. The conditions for the development of cyclones in the tropics are best satisfied when large continents lie to the west, whose coasts trend northward and southward, with extensive seas to the east. Such, at any rate, are the geographic features that exist in the regions of the West Indies, of the Philippine Islands, of the China Sea, of the seas of India, of the region east of Africa in the vicinity of the islands of Madagascar, Mauritius, Réunion, Rodriguez, etc.

Normally there is a belt of heavy air (great center of action) of about 10° of latitude in width, lying just north of the tropics, which interposes an almost impassable barrier to the movement of cyclones northward. The region of greatest pressure of this belt is about the middle of the Atlantic Ocean. By August the heat of summer acting on the North American continent has raised the temperature of the air over the land much more than it has that over the water, and the land portion of the high-pressure belt is dispersed, leaving an opening for the escape northward of tropical storms, which form in the ocean on the southwest periphery of the great high pressure that so persistently remains central over the ocean. From this place of origin the hurricanes are carried northwestward by the general circulation of air outward from and around the big high. This grand summer circulation of the air of the Atlantic Ocean brings the tropical storms nearly or quite to our South Atlantic or Gulf States before they recurve to the northeast in pursuing their course around the great high.

This anticyclone of the ocean differs from those that have heretofore been described in this chapter, in the fact that it quite doggedly holds to nearly the same geographic position. It covers the whole tropical Atlantic, and as the currents of air spirally flow outward, in a direction that agrees with the circulation of the hands of a watch, they frequently break up into small cyclonic whirls of 100 to 300 miles in diameter on the outer rim of the large anticyclone, and especially along the southwest quarter of the rim. The air as it runs down through the anticyclone feeds the vortices that form at the outer boundaries of the high. The vortex may whirl with the violence of a hurricane, and it usually does; but in its course westward and then eastward it clings to the outer hems of its parent—the anticyclone, or great center of action.

The wonderful sweep of the West Indian cyclone is made clear by the statement that storms of August and September may form southeast of the Windward Islands, cross the Caribbean Sea, recurve in the Gulf of Mexico or near the South Atlantic coast, and pass northeastward over the Atlantic Ocean and be lost in the interior of Europe or Asia. The history of these storms and of all others over the oceans is learned by collecting and charting the daily observations from thousands of moving ships in connection with the observations of island and coast stations.

The Translation of Storms.—In the temperate zones cyclones and anticyclones drift toward the east at the usual rate of 600 miles per day, or about 37 miles per hour in winter and 22 miles per hour in summer; but there is no definite rule on which the forecaster can rely. Sometimes they move at twice this speed, and again at less than half of it, or, what is more embarrassing to the prophet, remain stationary for one or two days and die out. It is safest to assume that the velocity of translation of a storm will be the average of the two immediately preceding it, unless the distribution of air pressure over the continent is markedly different in the several cases. Cyclones and anticyclones usually alternate, but not always. At rare intervals a rain storm or a cold wave may be followed by an atmospheric action similar to itself, with only a narrow neutral area (saddle) between.

The most difficult weather map to interpret and make a forecast from is one that contains several partly developed cyclones and anticyclones, each of small area and little force. The most that can be said, then, is that the weather will be unsettled, no definite type of weather lasting more than a few hours.

Four sevenths of all the storms of the United States come from the north plateau region of the Rocky Mountains and pass from this subarid region eastward over the Lakes and New England, producing but scant precipitation. The greater number of the remaining three sevenths are first defined in the southwest States or territories. These nearly always can be relied on to cause bountiful precipitation as they move northeastward over the lower Mississippi Valley and thence to New England.

Droughts in the great wheat and corn belts and elsewhere eastward are broken only by cyclones that form in Arizona, New Mexico, or Texas.

Storms move faster in the northern part of the United States than they do in the southern portion, and their tracks migrate with the sun.

Chart 30 illustrates the courses of summer storms in the United States. The lines show the origin and the tracks of the centers of the cyclones for August during a ten-year period, the anticyclones following about the same lines. Adding the numbers at the ends of the lines and at the braces that inclose groups of lines, it is found that 83 storms either had their origin in the States or else came to them from the West Indies or passed up through the ocean near enough to affect the Atlantic coast. The influence of the high western plateau and its mountains in the formation of storms is illustrated by the fact that 57 of these storms had their inception along the mountain system that runs through Colorado, Wyoming, and Montana, and that none came in from the Pacific Ocean. August storms move at the rate of 16 to 26 miles per hour, or about 500 miles a day. Wherever the storms originate, they are seen to have a strong tendency ultimately to reach New England.

Now turn to Chart 31, which gives the storm tracks for February for a period of ten years. Against the 83 storms of August there are 98 shown for February for the same period—1884–1893. The tracks curve down farther to the south, many of them come in from the Pacific, and a large number form in Texas, but, like those of August, they finally pass over New England, which fact explains the variability of the weather of the latter region.

These storm tracks are further illustrated on Chart 32 for January and on Chart 33 for July. Storm tracks generally run in about the same direction as the isotherms. There is an excessive number of tracks that begin on the North American continent as compared with Asia. While a few cyclones enter the United States from the North Pacific Ocean, the majority of the cyclones that occur in the northern hemisphere in the summer originate on the North American continent and break up or dissipate in Europe, one branch near the Arctic Circle and the other in southeastern Europe.

As regards storm conditions, the year may be divided into three types in the northern hemisphere: December, January, February, and March are dominated by swiftly moving storms, swinging far to the south and carrying wide oscillations of temperature and general precipitation even to the northern boundaries of the tropics. June, July, August, and September, by ill-defined storms and a sluggish movement of them, with many local rains of small area, rather than general storms, while October and November are transition periods between the summer and the winter types, and April and May between the winter and the summer conditions.

At times there is an abnormal change in the rate of drift of the highs and the lows simultaneously over the eastern and the western continents and the intervening oceans that throws weather forecasts temporarily into confusion.

When winter has become well established there often develops a permanent high over the great plain between the Rocky Mountains and the coast ranges, which remains inactive for weeks at a time, lows and other highs passing down from the north along its east front without materially disturbing it. Its principal function is to stop the drift of storms into the continent from the ocean immediately west of it. In midsummer this high may be replaced by a stagnant low, and hot scorching winds blow steadily toward it for many days over the states lying east and southeast of the low, withering the wheat and corn of the central Mississippi and lower Missouri valleys. Charts 32 and 33 show the most frequent routes of storms in the northern hemisphere.

The influence of the area of high pressure in deflecting storms from their normal or usual course is set forth by Professor Garriott in his paper on " Tropical Storms in September." In this paper Professor Garriott divided the tropical storms of September into three classes, namely: First, those that recurved[1] east of the 65th meridian; second, those that recurved between the 65th and 90th meridians; and, third, those that passed west of the 90th meridian or reached the United States without a recurve. Of the first class of storms, all of which first appeared east of the 50th meridian or north of the 20th parallel, Professor Garriott observes that only two appeared far enough to the south to render their advance over or near the West Indies a probability, and that in every instance the westward movement of the cyclones which recurved east of the 65th meridian was apparently prevented by anticyclonic areas which moved eastward over the Southern States and obstructed the westward advance and forced a recurve to the northward. He states that the recurve of storms of the second class—i. e., those that recurved between the 65th and 90th meridians—was apparently due to the obstruction offered to a westward course by anticyclonic areas which had advanced over the west Gulf States. A large proportion of the third class of storms advanced westward from the eastern West Indies. On their arrival in about longitude west 80°, the average longitude in which September tropical storms recurve, the pressure over the west Gulf began to decrease and rain set in, while the interior eastern districts of the United States were occupied by an extensive area of high pressure. The centers moved toward the region of decreasing pressure and avoided the high and increasing pressure to the northward. When the pressure continued high over the eastern districts of the United States the storms were unable to recurve, and were penned in over Mexico or the Southwestern States. Similarly cyclones of this class that advanced northwestwardly toward the Middle or South Atlantic coast of the United States were apparently prevented from recurving by high pressure over the ocean to the northward and northeastward, and were forced upon the coast.

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[1] Changed their course toward the northeast instead of the northwest.

From the foregoing it appears that the effect of distribution of pressure in determining a storm's path is closely studied in practical forecasting.

Determining the Direction and Velocity of Storm Movement.—District Forecaster Edward H. Bowie, of the U. S. Weather Bureau, has devised a new method of estimating the future course and rate of translation of storms. He says:[1]

"It is manifest that the direction and velocity of storm movement could be determined were it possible to obtain correct values that would represent the pressure exerted upon a storm from all directions and the eastward drift of air at high levels that carries the storm with it. Working on this theory, effort has been directed toward obtaining a value that would represent the twenty-four-hour eastward drift from any given locality. To find this value it has been necessary, first, to determine the resultant of the pressure from all directions toward the storm center. To represent this pressure from all directions, lines radiating from the storm center to the north, northeast, east, southeast, etc., have been given, after considerable experimental work, a length of 1 centimeter for each tenth of an inch increase in barometric pressure along these lines, working with a map the scale of which is 160 miles to an inch, or that of the Washington weather map. The resultant of such lines, or forces, acting toward the storm center, which may be found by the rules governing the polygon of forces, will show the direction toward which the unequal pressure is driving the storm.

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[1] *The National Geographic Magazine*, June, 1905.

" If the pressure of the air from all directions toward the storm center be a factor in determining the direction and velocity of movement of a storm, it is obvious that this resultant, representing the value of and direction toward which the unequal pressure forces the storm, becomes one of the components that determine the storm's path.

" As the twenty-four-hour movement of any given storm is the effect of the forces that determine that movement, it follows that by using this resultant of pressure toward the storm center as one of the components which cause the storm to move along its path it is possible to find the other component of motion by resolving a force representing a storm's twenty-four-hour movement into its two components. One of these components, representing the pressure effect, being known, the other component, representing the eastward drift, may be found by the rules governing the parallelogram of forces. If there be a basis for this theory, it must necessarily be that the second component, representing the eastward drift, should have approximately the same direction and value for two or more storms in the same locality for any given month of the year, provided the appropriate value is given the pressure acting toward the storm center from all directions. This component has been found for a large number of storms, whose values when charted show an agreement that appears to be more than accidental or merely coincident.

" Having found the component representing the twenty-four-hour eastward drift, which component is apparently fairly constant in value for any particular locality from year to year for a given month and the resultant of the pressures exerted on the storm center from all directions, the value of which is a variable quantity, it is patent that the direction and amount of movement of a storm is the resultant of these two forces. Thus, for instance, a December storm central in Colorado, subject to a pressure that tends to force it southward 400 miles in twenty-four hours, is during the same period being carried eastward 450 miles by the flow of the upper currents. It is evident that the storm's actual path will lie between the two lines representing the eastward drift and the pressure that forces the storm to the south, the resulting movement being almost due southeast and a distance of approximately 600 miles.

" From a study of storm movement along the lines outlined above it is apparent that the rate and direction of movement of a storm in relation to its normal movement is governed by this variable component, representing the deflective force, or the resultant of the pressure exerted on the storm from all directions. When this deflective force is acting in conjunction with the eastward drift the storm's rate of movement will be accelerated, and when in opposition the storm's progress will be retarded. It appears that in nearly all instances the storm increases in intensity when this component, representing the pressure of the air toward the storm center, is acting to the left of the normal direction of advance, but when toward the right the storm, as a rule, will decrease in intensity.

" Of course the application of the method is limited when the storm center is near a region from which no pressure observations are available —as, for instance, the storms that move along the Canadian border. In cases where there are a number of ill-defined storm centers it is not always possible to determine which center will become the primary one and which centers will be dissipated, and therefore there is more or less doubt whether the deductions will be borne out by subsequent events. In nearly all instances involving exceptions the error in predetermining the movement of the center is apparently due to inability to determine the exact values that should be used to represent the pressures toward the storm center from the several directions.

" The values determined by the methods used in the research along the lines indicated above are necessarily approximations only, and therefore tentative."

Tornadoes.—The conditions most essential to the formation of a tornado at a given place are as follows: (1) A cyclone or area of low pressure, the center of which is to the north or northwest, with a barometric pressure not necessarily much below the normal; (2) a morning temperature of 60° to 70°; (3) great humidity; and (4) that the time of year be March 15th to June 15th.

Tornadoes Not Increasing.—It is probable that the number of these storms is not increasing; the breaking of the virgin soil, the planting or the cutting away of forests, the drainage of land surfaces by tiles, the stringing of thousands of miles of wire, or the laying of iron or steel rails, have not materially altered the climatic conditions or contributed to the frequency or intensity of tornadoes. To be sure, as towns become more numerous and population becomes more dense, greater destruction will ensue from the same number of storms.

Relation of Tornado to Cyclone.—It is not possible with our present knowledge of the mechanism of storms to forewarn the exact cities and towns that will be visited by tornadoes without alarming some towns that will wholly escape injury; but we know that tornadoes are almost entirely confined to the southeastern quadrant of the cyclone, and that when the thermal, hygrometric, and other conditions are favorable, the region 300 miles southeast from the cyclonic center is in the greatest danger.

It is desirable to make clear the difference between the cyclone and the tornado. The majority of the press and many persons who should know better use these terms as synonymous. The cyclone is a horizontally revolving disk of air of probably 1,000 miles in diameter, while the tornado is a revolving mass of air of only about 1,000 yards in diameter, and is simply an incident of the cyclone, nearly always occurring in its southeast quadrant. The cyclone may cause moderate or high winds through a vast expanse of territory, while the tornado, with a vortical motion almost unmeasurable, always leaves a trail of destruction in an area infinitesimal in comparison with the area covered by the cyclone.

How the Tornado Differs from the Thunderstorm and Why it Occurs in the Spring.—The tornado is the most violent of all storms, and is more frequent in the central valleys of the United States than elsewhere. It has characteristics which distinguish it from the thunderstorm—viz., a pendent, funnel-shaped cloud and a violent, rotary motion in a direction contrary to the movements of the hands of a watch, together with a violent updraft at the center.

It is well to inquire if a satisfactory reason can be given for the occurrence of these violent agitations of the atmosphere mainly during the spring and early summer, and usually only in the southeast quarter of the cyclone. In answer it may be said that an hypothesis can be formulated that fairly well satisfies the requirements of the case.

The solar heat waves reach the earth and warm its surface, but the absorbed heat does not penetrate to any great depth. The land therefore retains the heat near the surface and quickly and freely radiates that which it has absorbed. The atmosphere, which is a poor conductor, is thus rapidly warmed at the bottom, but the heat is slowly conducted upward, and in the spring of the year the gaining intensity of the solar rays and the increasing hours of sunshine warm a thin stratum of air next the earth to an abnormal temperature in comparison with the stratum next above, which still retains the cold of winter. This abnormality is accentuated in the southeast quadrant of the cyclone, wherein southerly winds still further add to the heat of the lower stratum and increase the humidity. An unstable condition thus ensues, in which heavier air is superposed on lighter and much warmer air. This unstable equilibrium is more often relieved by the breaking through, here and there, of masses of the heavier air and the ascent of the lighter together with a *horizontal* rolling along the surface of the earth; these are *thunderstorms.* But at times a narrow *vertical* whirl is set up which develops great vortical energy; this is the tornado. The tornado also may be caused, and many times is, by the cyclone whirling together on the same level the cold currents from the northwest and the warm ones from the southeast, especially at an elevation of a few thousand feet, in the interior layers of the cyclone. The vortex then burrows downward to the surface of the earth, or dances along with the tail of the funnel whipping from side to side, and touching only the high places or nothing at all.

Tornadoes' Direction and Most Frequent Hour.—Tornadoes mostly occur between 2 and 5 in the afternoon, and generally move from the southwest to the northeast; their tracks may vary in width from a few hundred feet to one mile; their velocity of translation is usually about that of an express train; their speed of gyration can be measured only approximately, but it is sufficient often to drive straws into the bark of trees. A roaring like the sound of many express trains accompanies the tornado, whose track is usually 5 or 10 miles in length.

There is a wide variation in the number of tornadoes that occur during the years. Chart No. 34 shows the location and the direction of movement of all the tornadoes of a year of small number, and Chart 35 shows the result of a year of great frequency.

Floods.—With our many thousands of miles of navigable rivers flowing through one of the most extensive and fruitful regions of the world, daily forecasts of the height of water in the various sections of each river are of enormous benefit to navigation, and the warnings issued when the precipitation is so heavy as to indicate the gathering, during the near future, of flood volumes in the main streams are often worth many millions to navigators and to those having movable property on low grounds contiguous to the streams.

The feasibility of making accurate forecasts as to the height of water several days in advance at any station of the system is no longer questioned, and at stations on the lower reaches of large rivers one to three weeks' forecasts are feasible. The forecaster at each river center considers the rainfall, the temperature, the melting of snow, if there be any, the area and slope of the watershed, and the permeability of the soil. From a study of floods in former years he knows the time necessary for the flow of the water from the tributaries to the main stream and the time required for the passage of the flood crests from one city to another. The forecasts are, of course, empirically made, but still they are sufficiently accurate to possess great value to the people of the river districts.

From data that now covers many years at a large number of stations the following general relations have been deduced: The time it takes high water to pass from Pittsburg to Wheeling is one day; from Pittsburg to Parkersburg, two days; from Parkersburg to Cincinnati, three days; from Cincinnati to Cairo, six days; from Cairo to Vicksburg, seven days, and from Vicksburg to New Orleans, four days. The time, therefore, from Pittsburg to the Gulf is twenty-two days. Similar general relations concerning the movements of other rivers have been determined. Since the time is so great and the movement of high water is slower than the current, it follows that many interfering conditions may arise, tending to retard or accelerate the passage of the crest of the flood wave. No absolute rule is, therefore, possible; but the forecasting of the exact flood stage many days, or even weeks, in advance at important river stations is of such frequent occurrence as to indicate that, although the forecasts are empirically made, they have a substantial commercial value.

Each forecaster in charge of a river center has a definite section of the river system to watch and for which he must forecast. He receives the necessary telegraphic reports of the daily rainfall that has occurred over the tributaries to his river district, reports of the gauge readings nearer the source of the main river than his own station, and gauge readings from many of the tributary streams. He is familiar with the area of the catchment basin from which his rainfall reports are received, the contour and configuration of the surface, and the permeability of the soil.

A slowly falling rain of considerable amount on a nearly level and permeable soil may cause little rise, while a rapidly falling rain of the same amount on an impermeable and greatly inclined surface will gather quickly in the channels of the tributaries and soon become a rushing torrent in the main stream.

It is thus seen that many modifying conditions must be taken into consideration. The forecaster studies the history of previous floods under various temperatures and absorptive conditions of soil. He knows that the rainfall may be augmented by the melting of snow, if any there be on the ground, and that the temperature is an important factor in the flood; that on a frozen soil, under moderate heat, the entire precipitation, plus meltage, may flow away without appreciable absorption or evaporation and create higher water in the rivers than would be the case if the soil were open, and that an unfrozen but saturated soil presents to the flowing water practically the same surface, so far as the latter affects the flood, as a frozen soil.

Of the precipitation that is absorbed a part is evaporated, a part taken up by vegetation in making its growth, and the remainder sinks to the impervious rock, which lies at no great depth below the surface. It slowly follows the slope of the rock, and gives rise to the springs that supply the steady flow of the streams and rivers. This portion of downpour, while unimportant in the causing of floods, needs to be considered by the river forecaster, for an abundance of well-absorbed rains during the spring and early summer means the maintenance of fair stages in navigable rivers during the usual low-water season, and forecasts of low-water stages are nearly as important to commerce as the prediction of flood heights. In brief, floods have their origin in the surface discharge, while the low-water flow of streams is mainly due to the underground waters.

The *zero* of a river gauge is placed at the level of the lowest water known, and if at any subsequent time a stage still lower is recorded it is read as a minus quantity.

The *danger line* varies with the locality. On the Ohio River, on account of its narrow channel and its precipitous banks, the water must show vertical rises varying from 30 to 50 feet before the danger line is reached. At Cincinnati the danger line is 45 feet above the zero of the scale, and a height of 71 feet has been recorded. On the upper Mississippi the danger lines average about 15 feet above zero, but from St. Louis to Vicksburg they average about 35 feet, while at New Orleans the danger limit is but 13 feet above zero.

The Effect of Vegetation on the Flow of Streams.—The *regimen* of a river is the history of its movements and their causes. It may be modified by a change in surface conditions. Cultivated ground allows a much greater absorption than wild prairie soil, and therefore holds in storage and conserves the supply for springs and streams after flood seasons have passed. It is therefore probable that the extension of the methods of civilization has slightly reduced the intensity of floods in the plain regions, notwithstanding the cutting away of forests. It may be that deforestation has increased the intensity of floods in small constricted areas of mountain districts, which are usually small in comparison to the total area of each watershed; but where forests are cleared and kept clear, the hand of the husbandman keeps the surface so broken and permeable, or so covered with growing vegetation, that it is about as good a conserver of the rainfall as the forest-covered regions, and, except in areas too small to have an important effect on floods, Nature will at once begin to reforest a region that has been cleared. Certain it is that the hydrographs of the principal rivers of the United States do not show that the high waters are higher now or longer continued, or that the low waters are lower or of longer duration than they were half a century ago.

BIBLIOGRAPHY

ON FORECASTING

Abbe, Cleveland, "Preparatory Studies for Deductive Methods in Storm and Weather Predictions," Washington, 1890. (United States Signal Office, *Annual Report of the Chief Signal Officer for 1889.* Appendix 15.)

Bebber, W. J. van, "Handbuch der ausübenden Witterungskunde. Geschichte und gegenwärtiger Zustand der Wetterprognose," Stuttgart, 1885–86, 2 vols. Vol. 1 is a history of weather forecasting from the earliest times; Vol. 2 an exposition of modern theory and practice.

Garriott, E. B., "Long-range Weather Forecasts," Washington, 1904. (United States Weather Bureau, *Bulletin 35.*)

Garriott, E. B., "Weather Folklore and Local Weather Signs," Washington, 1903. (United States Weather Bureau, *Bulletin 33.*)

Moore, Willis L., "Weather Forecasting: Some Facts Historical, Practical, and Theoretical," Washington, 1899. (United States Weather Bureau, *Bulletin 25.*) Reprinted from *The Forum*, May, 1898.

Scott, Robert H., "Weather Charts and Storm Warnings," 3d ed., London, 1887.

ON STORMS

Algué, José, "The Cyclones of the Far East," 2d ed., Manila, 1904. (Philippine Islands, Weather Bureau, *Special Report of the Director.*)

Bigelow, Frank H., "Storms, Storm Tracks and Weather Forecasting," Washington, 1897. (United States Weather Bureau, *Bulletin 20.*)

Davis, William Morris, "Whirlwinds, Cyclones and Tornadoes," Boston, etc., 1884. ("Science" series.)

Doberck, W., "The Law of Storms in the Eastern Seas," 4th ed., Hongkong, 1904. (Hongkong Observatory, No. 3.)

Eliot, Sir John, "Handbook of Cyclonic Storms in the Bay of Bengal for the Use of Sailors," 2d ed., Calcutta, 1900–1. 2 vols.

Finley, John P., "Tornadoes. What They Are and How to Observe Them; With Practical Suggestions for the Protection of Life and Property," New York, 1887.

Garriott, E. B., "Storms of the Great Lakes," Washington, 1903. (United States Weather Bureau, *Bulletin K.*)

Garriott, E. B., "West Indian Hurricanes," Washington, 1900. (United States Weather Bureau, *Bulletin H.*)

Great Britain, Meteorological Office, "A Barometer Manual for the Use of Seamen; with an Appendix on the Thermometer, Hygrometer, and Hydrometer," 5th ed., London, 1905. (*Official*, No. 61.)

Hazen, H. A., "The Tornado," New York, 1890. (Fact and theory papers.)

ON FLOODS

Morrill, Park, "Floods of the Mississippi River," Washington, 1897. (United States Weather Bureau, *Bulletin E.*)

CHAPTER XIV

OPTICAL PHENOMENA IN METEOROLOGY

THE colors of the sky and clouds depend principally on the presence of water vapor, clouds and dust in the air; but there is one important exception that we will consider first—namely, the blue and associated tints of the clearest atmosphere.

The Blue Sky.—The researches of Lord Rayleigh have made it seem almost certain that we should have an azure sky even without the presence of moisture or dust, because the individual molecules of oxygen, nitrogen, and other gases, whose diameters are less than the wave-length of the light falling upon them, diffuse it according to the law that the ratio of the scattered to the incident light is inversely proportional to the fourth power of the wave-length.

Probably in many cases selective absorption, especially of the blue, and selective reflection from the earth and from the clouds, modify the colors of the sky. There is also some evidence of fluorescence in the upper atmosphere.[1] Because of the inverse fourth-power law an excess of blue light emanates in all directions from every gaseous particle and fine dust-mote in the atmosphere, and the result is the blue light of the sky.

Always Dark at the Top of the Atmosphere.—When an observer is on the summit of a mountain or when he ascends in a balloon, the bluish tint becomes feebler in proportion as the mass of the air above him diminishes and the blue sky gradually becomes darker or blacker until the brighter stars begin to be visible and the zenithal portion of the sky has the color of late twilight, and, granting its possibility, if one should ascend to the upper limits of the atmosphere, where there is nothing to diffuse the light rays, he would find himself surrounded by total darkness.

Whitish Light Reflected only from Large Particles of Lower Atmosphere.—On the other hand, as the observer occupies a lower position, and especially when the aqueous vapor increases, the color of the sky becomes whitish, as it usually is in equatorial regions. This is apparently due to the presence of cloud or other particles that reflect all colors more or less equally, so that the diffuse light more nearly resembles that of the sun itself.

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[1] For an interesting *résumé* of this subject, with references to many valuable papers, see "Theories of the Color of the Sky," by E. L. Nichols, *Physical Review*, June, 1908.

The Reds, Yellows, and Tints of Green.—In the lower half of the atmosphere there are frequently larger particles, probably of aqueous vapor, dust, and smoke that absorb the blue, but transmit the red, so that after sunset or before sunrise beams of reddish light permeate the atmosphere above our heads. When we look at this light directly above the sun and at an altitude of from 10° to 20° above the horizon, while the sun is 10° or 15° below the horizon, we see a pinkish blotch on the sky; on either side of this for a long distance we perceive a delicate green tint shading above into the blue and below into the yellows and reds. Lower down nearer the horizon, both before and after sunset, we frequently see horizontal bands of both red and yellow, the red being more prominent in warm, moist air, and the yellow in cold, dry air. In very dry air, such as occurs in areas of high barometric pressure and cloudless skies, the color is a light lemon-yellow, but this is only seen in temperate and northern latitudes, while the deeper yellows and reds prevail in the tropical regions and in our moist summers and on the advancing fronts of areas of low pressures or storms.

Paintings by eminent artists, such as Turner, often give us elegant representations of the lurid red that precedes a storm on the British coast or a hurricane or typhoon in the tropics. In such cases, the sun being near the horizon, its light reaches the observer's eye after passing through many miles of the denser moisture of the lower air, or after being reflected from the particles of the lower clouds and has lost first the blue and then the yellow portion of the spectrum, until only the red remains.

The penetration through the atmosphere of long light waves and the absorption of short ones causes the change in the color of the sun and moon from a brilliant white, when at considerable elevations, to an orange or red when on the horizon. The red or copper color of the moon, when totally eclipsed, is due in part to this absorptive power and in part to the refraction of the earth's atmosphere.

Effect of Volcanic Dust on Color of Sky.—An unusual illustration of selective absorption was given on the occasion of the most violent volcanic eruption of historic times—that of Krakatoa—on August 27, 1883, when an immense volume of dust and aqueous vapor was thrown to a great height in the atmosphere above the Straits of Sunda. The antitrades spread this over the northern hemisphere, and winds higher up in the tropics carried it westward around the world and formed a layer from 5 to 15 miles above the earth's surface, consisting undoubtedly of minute particles. During the daytime the sun's disk appeared red, green, or blue, according to the thickness of the stratum through which the observer viewed it. The sun was also surrounded by a halo of 15° radius, known as "Bishop's Ring," after Sereno Bishop, of Honolulu, who first described it. This ring certainly was due to the diffraction of light penetrating through the layer of fine particles of ice or dust. After sunset, and by virtue of the diffusion of red light by this layer of particles, the whole western sky, even to near the zenith, glared with a lurid red as though lighted up from some great and distant fire.

These remarkable sunsets continued, slowly diminishing in brilliance, through the years 1884 and 1885 in temperate latitudes, while their northern limit advanced slowly toward the pole, showing that minute particles of solid matter may float for years in the high upper atmosphere, so long as slowly rising currents buoy them up. Isolated clouds of such material may always be floating in the upper atmosphere and may give rise to the noctilucent or night-shining clouds that are occasionally observed at great altitudes when the observer looks northward in midsummer.

In addition to the sky colors due to aqueous vapor, there are tints due to the presence of floating dust particles. The sky tint is not the color of the dust proper, but is determined principally by the irregularity in the sizes of the particles and by their translucency. The air and the particles form a nonhomogeneous mixture, that in large measure cuts out the shorter waves, while transmitting the longer ones so that the residual color is reddish, yellowish, or brownish. As the dust increases, the browns become ashy gray and darker, and eventually all light is lost as it is in the midst of dust clouds, dust showers from volcanoes, and dense thunder- and tornado-clouds.

Polarization of Sky Light.—When a beam of sunlight reaches the atmosphere some of it is scattered in all directions by the finer dust, and even by the gas molecules. This scattered light is plane polarized, and therefore cannot freely pass through a Nicol prism except when the latter is set in one or the other of two particular positions about its axis that differ by 180°. A quarter of a turn about its axis, in either direction from these positions, will so set the Nicol that none of the polarized light can get through. The light scattered at right angles to the direction of the incident beam is completely polarized—that is, the Nicol can be so set that none of it can get through, while that which leaves in other directions is but partly polarized, or the Nicol, however set, will let through some of it.

The sunlight that reaches the observer from any point in the sky has a polarization that depends primarily on the position of that point relative to the sun and to the zenith. There are two regions, or oval zones, one around the sun and the other around the antisolar point, where we may say that the positive and negative polarizations balance each other, forming so-called neutral bands.

Polarization diminishes as the whiteness of the sky increases and polarization phenomena are not noticed at all when one observes the light reflected from a cloud. If this cloud were a polished surface these phenomena would undoubtedly be present, but it is made up of a mass of particles, each of which neutralizes the effect produced by some other particle. However, if we look at a distant small cloud through a Nicol prism and rotate the prism so as to cut off all the polarized light that comes to us from the intervening atmosphere, we shall see the cloud much brighter, clearer, and sharper in all its details. If we look through the prism at a cirrus cloud high up in the sky we may thereby cut off nearly all the polarized light and see details otherwise invisible. The same result is accomplished if a large reflecting polariscope is used instead of the little Nicol prism. The best photographs of cirri have been taken by pointing the camera at their images in a black mirror, thereby cutting out the polarized sky light, and rendering the background relatively dark.

In the study of many substances polarized light offers a great variety of beautiful phenomena, but it yields nothing comparable in meteorology, except only the mild phenomena developed by its use in the examination of ice crystals, snow crystals, and hail. The structure and mode of growth of crystals of ice is partially revealed by the strains that exist within them, and the position of these strains is determined by the aid of polarized light. The most homogeneous bodies show polarization phenomena when subjected to strains.

Glories, or Coronæ.—The glories, or coronæ, of a few degrees in diameter, seen around the sun or moon, exhibit a succession of colors, the red being on the outside of the circle and the blue on the inside. These colors are produced in accordance with an optical principle of interference of waves of light, and in this particular case the phenomena themselves are known as diffraction. In accordance with this principle, when two beams of light intersect at an extremely small angle, the point of intersection, being equally affected by the two systems of waves, may become a source of light or of darkness, according as the waves reënforce or neutralize each other. The little spaces between the particles of all hazy clouds allow these separate beams of light to pass through, and as they converge upon the retina they interfere and produce alternate light and dark bands. The bands are broader and the radii of the coronæ are larger in proportion as the cloud particles are smaller; hence the angular diameter of the corona is an index to the size of the particles of the clouds. A thin layer of lycopodium spores, such as may be obtained from any druggist, spread upon a glass surface and held before the eye shows beautiful concentric circles of color around any light if viewed through it; bunches of wool, cotton, or other fibers do the same. By measuring the apparent diameter of these circles, as in Young's eriometer, one may determine the linear diameters of the particles themselves. This problem was first proposed by Fraunhofer, the famous maker of achromatic telescopes.

Everyone is familiar with the colored coronæ surrounding a bright object, as seen through a pair of spectacles freshly and slightly bedewed with moisture. These colors are due to the same principle of optical interference and are entirely analogous to those seen through a fog. Such circles may be seen around the sun almost any day of the year if we view it by reflection from some poor reflecting surface, like water, in order to eliminate the blinding glare of the sunshine.

In the case of the largest corona, known as Bishop's Ring, the average diameter of the particles of this ring by diffraction was calculated to be about 0.00015 of an inch.

A brilliant series of experiments was begun by Dr. Carl Barus for the Weather Bureau in 1891, and has been continued by him ever since, leading up to new views in regard to the atmospheric vapor. He calls this subject "cloudy condensation," the idea being to determine by what process the cloud particles form and how they join together to form rain. He has conveniences at hand for filling a small tube with any kind of vapor in any state of condensation.

A beam of light is allowed to pass through it, and as condensation takes place it is immediately accompanied by magnificent displays of color. The size of the particles may be determined by the color and order of the spectrum, and the total range of sizes observed by him lies between 0.0004 and 0.00001 of an inch. These studies by Barus go far to show that the colored clouds and colored suns are truly interference phenomena—not necessarily interference by diffraction.

Rainbows.—When direct sunlight falls upon a transparent sphere, such as a raindrop, some of it is reflected from the outer surface in all directions, and some of it refracted to the interior of the drop, where it suffers from one to many internal reflections, with more or less loss, dependent upon the angle of incidence, at each place of reflection.

The refraction splits the original light into all its elementary colors, and these are sent out practically in every direction. That part of the light which leaves the drop in a diverging manner is spread over an area that increases as the square of the distance, and hence soon becomes imperceptible. The same is true also of that part which leaves the drop in a converging manner, because beyond the point of intersection it, too, becomes diverging.

There are a few directions, however, in which the light leaves the drop in very nearly parallel beams, and along which it travels with but slightly diminished intensity. This light of practically constant intensity is the light of the rainbow.

The several colors composing the original sunlight are refracted unequally, and therefore separated. Also, since the drops are spherical, whatever angle exists at one of them between the incident solar ray and a given colored ray that goes to the observer, must obtain for all other drops that do the same thing. Consequently, the rainbow is along the circumference of a circle whose center is on a straight line with the sun and the eye of the observer. Hence no two persons see strictly the same rainbow. One sees the light from one set of drops, while another sees that from a different set.

Very generally two bows are seen simultaneously. The one with the smaller radius, the primary, is the brighter and is due to light that enters the upper portions of the drops, and after one internal reflection leaves their lower portions. The larger and fainter bow, the secondary, is due to light that enters the lower portions of the drops, and after two internal reflections leaves their upper portions.

The outer edge of the primary bow is red and the inner violet, while in the secondary the reverse is the case.

Accompanying both the primary and the secondary, which are some distance apart, are often seen from one to many supernumerary bows, due to interference phenomena.

For a full discussion of the rainbow, which requires the free use of mathematics, the reader must consult some advanced treatise on optics.

Halos.—The same so-called theory or principle of interference in optics applies to all halo phenomena. These halos, whether formed by the action of simple crystals of ice or by that of complex snowflakes, give rise to a large variety of optical phenomena, most of which were well explained by Bravais in his memoir on halos, published in Paris in 1845, which has been the source of inspiration for many subsequent writers.

Among more recent students of this subject, Professor Pernter, of Vienna, stands preëminent. When the vapor of the atmosphere cools quietly it frequently forms minute spheres of water, which remain liquid even far below the freezing temperature. Such spheres of water have been observed at temperatures of 20° below zero C., and there is no reason to think that this is the limit. If, however, the air is in motion rapidly, or if these spheres of water be touched, they immediately turn to ice with a slight evolution of heat. These minute crystals of ice are called spiculæ, or needles, and have almost invariably the simple form of regular slender hexagonal prisms capped by hexagonal pyramids.

One would naturally expect these needles to fall rapidly toward the earth with the sharp end pointed downward, but their fall is appreciably resisted by the atmosphere and they are set in rapid rotation around their longer axes. By virtue of this rotation, the longer axis soon assumes a horizontal position, that of greatest stability, and the crystal falls to the ground, rotating or oscillating slightly upon its horizontal axis. If, however, the crystal is not perfectly symmetrical, and especially if two or more are joined together, as at the beginning of the process of formation of snowflakes, then the crystals may fall at almost any angle, but always in a state of steady and rapid rotation. By following up the geometrical relations of the facets of the crystals to the axis of rotation and to the vertical along which they are falling, it becomes possible to show that the observer, looking through a filmy cloud of such crystals, would see in one part of the sky a halo, in another part an arc of light, and in other directions bright spots like the sun, all of them arranged symmetrically with regard to the sun and the observer's zenith. This resulting complex arrangement of circles and spots is known as a complete halo. It is rare that all possible combinations are seen at any one time, but on several occasions solar halos have been recorded that corresponded very nearly to this ideal. Three of these have become classic—namely, that observed by Scheiner at Rome in 1630, the halo observed by Hevelius at Danzig on February 20, 1661, and that observed by Löwitz at St. Petersburg on June 18, 1790.

The drawings of these halos are given in Hellmann's "Neudrucke," or series of reprints, from which the accompanying reproductions have been taken (Figs. 79, 80, and 81).

In general, halos do not appear at their best in very cloudy or thick, hazy weather, but when the atmosphere is clear, with only a thin veil of falling crystals spread between the observer and the sun. Although the halo phenomena appear to belong to some very distant upper layer of air, yet practically they often originate in the very lowest layer. They depend simply upon the fact that there is a myriad of ice crystals, some in a position to make one part of the halo and some in a position to make another part, with plenty of particles substituting for others as fast they fall out of place.

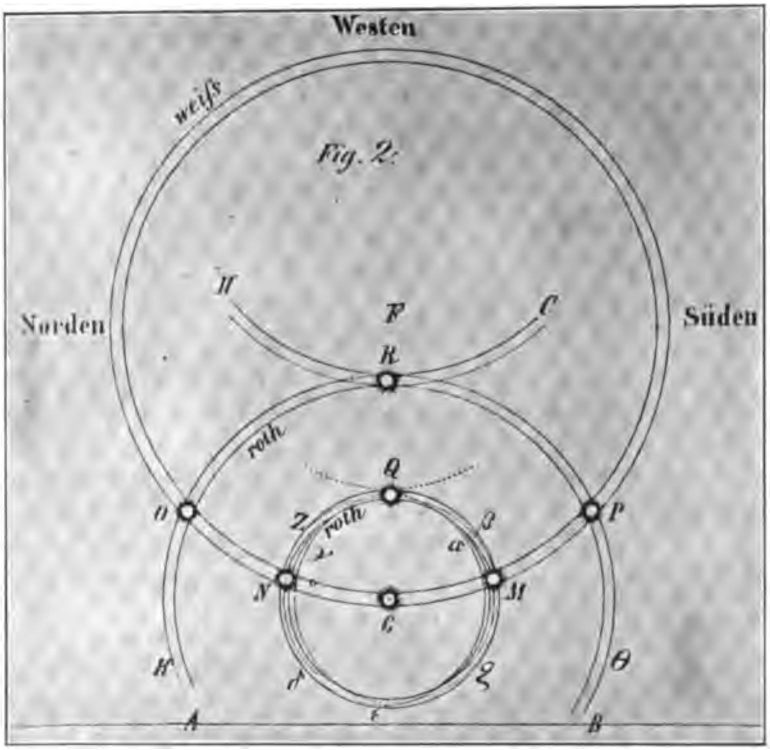

FIG. 79.—COMPLETE HALO OBSERVED BY SCHEINER AT ROME, 1630.

(*a*) The most common of the halos is the one of 22° radius, or a small ring around the sun or moon; this circle has a red border on the inside edge, or next to the sun, followed by a little yellow or green, and with bluish white on the outside. The measured angular radius is not always 22°, but varies between 21° 12′ and 22° 40′, the average being slightly less than 22°.

(*b*) Adjoining the halo of 22°, tangent to it at the upper and lower edges, but, in general, outside of it, there appears an elliptical halo whose longer radius is about 25°.

(*c*) Entirely outside of these is a great ring, or halo, of 46° radius, and outside of that a halo of 90°, both of which are rarer, and the last

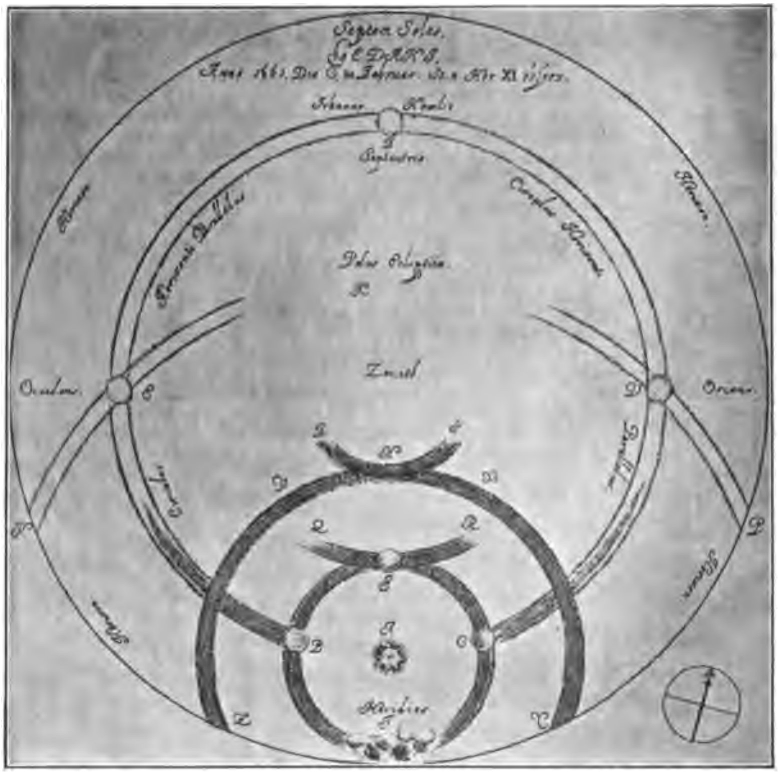

FIG. 80.—COMPLETE HALO OBSERVED BY HEVELIUS AT DANZIG, 1661.

especially rare. The latter is supposed to be colorless, but the former has the interior ring red, and the exterior possibly is blue, but it is more common that the red merges into yellow and that no outer colors are visible.

(*d*) We come now to several tangential arcs or bows, and the first is that which is tangent to the upper halo of 22°; this is usually of the most brilliant rainbow colors.

(*e*) There is another similar or tangential bow at the lower edge, but not so often visible, since the sun is too near the horizon.

(*f*) Then again there is a tangential arc at the lower edge of the circle of 46° radius, but this can be seen only when the sun is 46° above the horizon. It, also, is a colored bow, with the red on the side next to the sun, and seems to be parallel to the horizon.

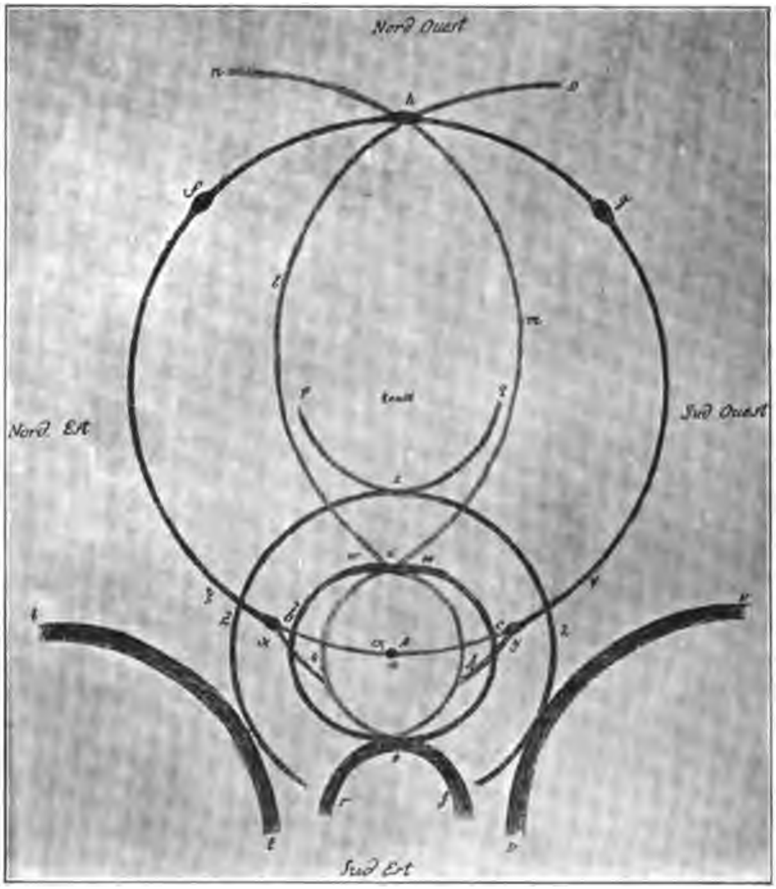

Fig. 81.—Complete Halo Observed by Lowitz at St. Petersburg, 1790.

(*g*) Again, there is a circular arc that sometimes appears near and surrounding the zenith, and also sometimes intersecting the halos of 22° and 46°.

(*h*) Besides these halo circles there are bright spots, or sundogs, which belong respectively to the circles already described.

The intersection of any two features is sometimes spoken of as a mock-sun, and these may be on either side of the true sun or on either side of the antisun. The latter is on a horizontal circle, passing through the primary mock-sun, but is distant from it 180° in azimuth. There are usually two mock-suns, one on each side of the true sun, and two also where the halo of 22° intersects the horizontal circle. It can happen that only the mock-sun, or the horizontal circle, or the halo ring of 22° shall be present. In general, these mock-suns are the most highly colored of the halo phenomena.

The first to explain the origin of these halo phenomena was Descartes, who suggested that they might be produced by star-shaped crystals of ice thicker in the middle than at the edges, and therefore producing rings that are larger in diameter in proportion to the thickness of the ice. Huyghens came much nearer to the truth, but Mariotte was the first to perceive that crystals of ice were involved in their production. The greatest success attended the labors of Bravais, who prepared artificial models of crystals and studied them by giving them rapid rotation around their axes.

Mountain Mists and Specters.—An interesting phenomenon is seen by observers standing on a mountain top at sunrise or sunset, when the shadow of the mountain, or what appears like it, suddenly starts into view. The dark shadow is bounded on either side by ashen or rosy tints, and rises as the sun descends, or *vice versa.* A still more startling cloud effect is known as the Specter of the Brocken, as it was first described as having been observed on the famous mountain of that name in Germany. It is seen when the sun shines past the observer, and he sees his own shadow cast upon the clouds, or, more often, on the thin fog, while a circle of glory appears to surround his own head. The most beautiful pictures of these glories have been published in connection with descriptions of balloon voyages, as the aeronaut sees a similar but still more brilliant glory surrounding his shadow when projected upon the top of a cloud. These glories, or shadows, are, of course, due to the reflection of light from the interiors of the cloud particles, combined with the phenomena of interference, just as in the case of glories around the sun or moon, which are formed by light that has passed through the drops without reflection. But the glories seen by the aeronaut are more perfect than those seen by the ordinary observer, because the particles on the upper sides of the clouds are more regular in size.

An observer inside a bank of fog usually reports that the sky is cloudy and of a gray tint, since this is about the character of the light that penetrates the bank of fog, unless it be a very light fog or haze, or he be near its surface. There is quite a distinction between the tints seen inside a wet fog or cloud and those seen inside a dry fog or haze, such as is always associated with the harmattan on the west coast of Africa. In the latter case the sky has a chalky-white tint and the air is very dry. We attribute the whitish tint not to any moisture, but to the presence of innumerable fragments of microscopic diatoms or siliceous shells. The whitish color of the haze must be attributed to the reflection of light from their surfaces. A similar white haze occurs in air that is full of grains of pollen, or fine crystals of snow, or almost any other kind of small particles.

Although the clouds appear white in full sunlight, yet when illumined by the yellow and red rays that penetrate to them from the setting sun they form the most magnificent color displays that are to be found anywhere in nature.

The upper part of a tall cumulus is often a delicate pink, while the lower portion is ashen gray; and below that the blue and green sky tints may be visible. A decided pink or straw-colored yellow is often seen when looking at the dazzling white on the sunny side of a cumulus cloud. Apparently the surface particles of the cloud are being evaporated in the sunshine, and the adjacent layer of air is supersaturated with moisture at a relatively high temperature; possibly minute particles of water are present and modify the orange and pink tints that are spread in spots over the cloud. The tints are only seen when cumuli are sending up great thunderheads like explosions of steam boilers.

Still another color phenomenon is associated with the under sides of cumulus clouds, as in approaching thunderstorms, when the landscape beyond the cloud is brilliantly lighted by the sunshine; in such cases the observer may see patches of yellow or green on the lower side of the cloud, being light from the bright landscape beyond, reflected by the big drops.

Twilight.—As already explained, light, in passing through the atmosphere, is scattered to a greater or less extent by dust-motes, by moisture or cloud particles, and even by gas molecules. Therefore, light from the illuminated upper atmosphere reaches the earth even when the sun is decidedly below the horizon.

The sun moves along its daily path at practically a uniform speed for all parts of the earth and at all times of the year, so that the length of the arc traversed in half an hour is always and everywhere essentially the same. The distance, however, that this nearly fixed length of arc will place the sun below the horizon after sundown or before sunup will depend upon the angle between them. In the tropics, where this angle is nearly or quite 90°, the distance below the horizon clearly increases most rapidly, and twilight that fades away with increase in this distance is of short duration. In high latitudes, where the angle in question is not large, the horizon distance of the sun increases less rapidly, and therefore the twilight is of correspondingly longer duration.

Mirage.—It often happens that the air next the surface of a level desert plain becomes strongly heated and so expanded that it is lighter than the layers immediately above it. In this condition it will transmit rays of light at greater speeds than will the overlying denser air. Consequently, a ray of light from a distant elevated object may pass first to this heated stratum and there, by a process of gradual refraction, or, if the two layers are sharply separated, by total reflection, be turned up to the observer's eye, just as is the case in reflection from water, for which such layers of air are often mistaken. Any phenomenon of this general nature is called a mirage.

Irregularities in the unequally refracting (because unequally heated) layers of air produce corresponding irregularities in the resulting phenomena, to some of which are given specific names. The term mirage is commonly restricted to phenomena such as would be seen in a horizontal mirror placed at a level below that of the eye of the observer, while *looming* is a term restricted to the analogous phenomena that appear to come from reflection in a horizontal mirror at some level above the observer. The term Fata Morgana is a local (Italy and Sicily) name for any mirage, rather than a specific name restricted to some definite manifestation of the phenomenon.

BIBLIOGRAPHY

The only recent extensive general treatise on atmospheric optics is J. M. PERNTER and FELIX M. EXNER'S "Meteorologische Optik," Vienna, 1902–10.

E. MASCART'S "Traité d'optique" (3 vols. and atlas), Paris, 1889–94, devotes much space to meteorological optics. See especially vol. iii.

On optical effects of the Krakatoa eruption see:

ROYAL SOCIETY OF LONDON, "The Eruption of Krakatoa, and Subsequent Phenomena," edited by J. G. SYMONS, London, 1888.

For recent views as to the cause of the blue color of the sky see:

STRUTT, JOHN WILLIAM (Lord Rayleigh), "Scientific Papers," Cambridge, 1899–1903, vol. i, pp. 87–103; vol. iv, pp. 397–405.

Also an interesting communication by PROF. ARTHUR SCHUSTER on "Molecular Scattering and Atmospheric Absorption," *Nature*, London, vol. lxxxi, 1909, pp. 97–98.

CHAPTER XV

CLIMATE

Definition of Climate.—From the Greek word κλίμα, a slope or inclination. The term was used to denote the effect of the oblique rays of the sun on the temperature of the earth and its atmosphere. To-day it is applied to the summation of the atmospheric conditions as recorded for a long period of time; or, in other words, it is the totality of weather, while " weather " is the physical condition of the atmosphere at a given time, or during a limited period.

One may well speak of the weather of to-day, or of last month, or of some past year, but not of the climate of a day, a month, or a year. The climate of a place is ascertained by a study of its continuous weather records for a long period of years—the atmospheric pressure, the temperature, the rainfall and snowfall, the time and frequency of frost, the extremes of heat and cold, the direction and velocity of the wind, the amount of air that flows from different points of the compass, the amount and the intensity of sunshine, the humidity and transparency of the atmosphere, and its electrification. Climatology is to be considered as a subdivision of meteorology.

Hann, at the beginning of his " Handbook of Climatology,"[1] gives the following definition of climate:

" By climate we mean the sum total of the meteorological phenomena that characterize the average condition of the atmosphere at any one place on the earth's surface. That which we call weather is only one phase in the succession of phenomena whose complete cycle, recurring with greater or less uniformity every year, constitutes the climate of any locality."

The same writer presents an alternative definition, according to which climate is regarded as " the sum total of the meteorological conditions in so far as they affect animal or vegetable life "[1]; and this second definition brings into view the real standpoint of a majority of the writers on climatology, from the time of Humboldt to the present day.

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[1] HANN, J. "Handbook of Climatology" (Ward's translation), New York, 1903, p. 1.

While the existence of a purely physical climatology, taking account of all the meteorological elements without reference to their biological effects, has generally been recognized, the term *climatology* (i. e., the science of climate) has, in practice, most frequently been applied to the discussion of meteorological values in their relation to organic life, and especially to the life of man; and a corresponding restriction is observed in the customary application of the word *climate.* Thus we commonly refer to the climate of Labrador; less frequently to the climate of the Atlantic Ocean, which is but transiently the abode of man; and hardly at all to the climate of any portion of the free upper atmosphere.[2]

The terms *bioclimatology* and *anthropoclimatology* have been proposed to denote the discussion of climate in relation, respectively, to life in general and to human life in particular. The importance of these subjects justifies the attention that the climatologists have given to them.

Climatic Data and their Presentation.—The meteorological elements—pressure, temperature, humidity, etc.—are not very numerous, but the values of each for a given station may be summed and averaged in an endless variety of ways. Thus, given the mean daily temperatures at any station through a period of twenty years, we might, if there were any apparent object in doing so, combine these in groups of two, three, four, five, or more consecutive days, and compute the average of each group; or again, taking every third day of the series, we might compute the average variability of the temperature between selected days. Innumerable other possible combinations will suggest themselves to the student.

Thus we have an infinite variety of possible climatic data to choose from, and we perceive the need of adopting certain criteria to guide us in selecting the data that are most worthy of presentation in descriptions of climate. These criteria are mainly furnished by the requirements of biology and of the study of human affairs. One result of their adoption is that the meteorological elements assume an order of importance in climatology different from that which obtains in meteorology. Thus atmospheric pressure, which occupies so prominent a place in meteorology, is relegated to a subordinate position in climatology, because its fluctuations generally have no perceptible direct effects upon organic life.

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[1] *Op. cit.*, p. 3.

[2] Etymologically, *climate* is purely a geographical term, denoting each of the latitude zones into which the earth's surface was divided by the ancient geographers according to the length of the day at the summer solstice, this being determined by the slope (Greek κλίμα) of the earth's surface with respect to its axis of rotation. In each hemisphere there were twenty-four "climates" or zones between the equator and the polar circle, each corresponding to an increase of half an hour in the length of the longest day. Between the polar circle and the pole itself six additional zones were distinguished, each corresponding to an increase of one month in the greatest length of the day.

In order that the climatic statistics for various places may be mutually comparable, it is highly desirable that climatologists should agree as to which data are essential in the description of climate. Formerly there was much diversity of practice on this point, but a fair degree of uniformity has now been attained, mainly through the efforts of Dr. Julius Hann, whose " Handbook of Climatology " is accepted as a guide in the elaboration of climatic statistics.

The following enumeration of the principal numerical climatic data is largely based upon the recommendations of Hann, as interpreted by Prof. Cleveland Abbe in his " Aims and Methods of Meteorological Work."[1] Some notable additions are due to Professor Abbe himself—especially the data concerning subjective temperatures (No. 35) and cyclonic and anticyclonic weather (No. 36)—while the data of wind velocity have been enlarged to more fully express the results obtained with automatic registers, such as are used at all important stations in the United States. Of course such a list must be regarded as provisional, since the future development of the sciences affiliated with meteorology may lead to the inclusion of additional data not now recognized as important.

Principal Numerical Climatic Data.—1. The monthly and annual mean temperatures of the air.

2. The extent of the mean diurnal range of temperature for each month and for the year.

3. The mean temperature at the different observation hours, for each month and for the year, or at least the mean temperatures of an early morning hour, and of an afternoon hour about the usual time of the maximum.

4. The extreme limits of the mean temperatures of the individual months. Also, when there is a long series of observations (i. e., over twenty years), the mean variability of the monthly means.

5. The mean monthly and mean annual extreme temperatures, and the resulting nonperiodic mean monthly and mean annual ranges.

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[1] *Maryland Weather Service*, special publication, vol. i, pp. 265–267.

6. The absolute maximum and minimum temperatures observed within a given long interval of time. The length of this interval should be stated.

7. The mean variability of the temperature as expressed by the mean of the differences between consecutive daily means, and also by the frequency of changes of temperature of a given amount between these daily means—as, for example, changes for intervals of 2°.

8. The average limiting dates of frost in spring and autumn, and the number of days free from frost.

9. The elements of solar radiation, as measured by optical, chemical, and thermal effects. (Unfortunately, observations of the intensity of solar radiation have been made at comparatively few stations, and many of the earlier observations were made with unsuitable instruments; hence these data have not yet attained the prominence that they deserve in discussions of climate.)

10. The elements of terrestrial radiation, as measured by a radiation thermometer.

11. The monthly and annual mean temperature of the ground at the surface and at various depths. (The depths 3, 6, 9, 12, 24, 36, and 48 inches have been used in the United States.)

12. The monthly and annual means of the absolute quantity of moisture in the atmosphere. This is usually expressed by giving the vapor pressure.

13. The monthly and annual means of the relative humidity of the air.[1] (Relative humidity generally has a considerable diurnal range; hence it is desirable to give its average values for the hours of observation separately, as well as the daily mean.)

14. The total precipitation, as rain, snow, hail, dew, and frost, by monthly and annual amounts. (For some purposes it is more useful to give the annual amount, and the monthly amounts expressed as percentages thereof.)

15. The monthly and annual maximum precipitation in twenty-four hours and in one hour. (More detailed statistics of the extreme intensity of rainfall are valuable for agricultural and engineering purposes. Such are the records of accumulated amounts of rainfall for five-minute peri-

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[1] Several writers have advocated the use of the *saturation-deficit*—i. e., the difference between the observed vapor pressure and the maximum vapor pressure possible with the prevailing temperature—in addition to or in place of the relative humidity. See Hann's "Handbook of Climatology" (Ward's translation), pp. 49, 53–56.

ods, during the heaviest rain storms, as registered by an automatic rain gage.)

16. The average number of rainy days, for each month and for the year. (In countries using the metric system a " rainy day " or " day with rain " is variously defined as a day with 0.1 mm., 0.2 mm., or 1 mm. In England and America the critical amount is 0.01 inch. In British India a rainy day is one with at least 0.10 inch of precipitation. The earlier rainfall records for all countries generally recognized no minimum limit of rainfall for a " day with rain." [1])

17. The percentage of rainy days in each month or the probability of a rainy day.

18. Mean frequency of long dry and rainy periods (preferably given by seasons).

19. Average monthly and yearly snowfall, and number of days with snow.

20. Average dates of first and last snowfall; average duration of the snow covering.

21. Number of days with hail, for each month and for the year.

22. Number of days with thunderstorms, for each month and for the year.

23. Average number of clear, partly cloudy and cloudy days, for each month and for the year.

24. Average monthly and yearly cloudiness—i. e., the portion of the sky covered by clouds, generally expressed in tenths of the whole sky. (In addition to the daily averages of cloudiness it is advisable to give the averages for each of the hours of observation.)

25. Average monthly and yearly duration of sunshine, in hours and in percentage of the possible duration.[2]

26. The average number of foggy days, for each month and for the year. A statement as to the total duration of fog, in hours, is also desirable.

27. Average number of nights with dew, for each month and for the year.

28. Monthly and annual means of wind velocity (miles per hour or

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[1] For further particulars on this subject, see Brückner, "Ueber die Methode der Zählung der Regentage," in *Meteorologische Zeitschrift*, iv, 1887, pp. 241–252.

[2] On the relation between duration of sunshine and amount of cloudiness, see Hann, "Lehrbuch der Meteorologie," 2d ed., Leipzig, 1906, p. 215. These two data do not supplement each other exactly.

kilometers per second) or of estimated wind force (Beaufort or other scale).

29. Average and absolute maximum wind velocity, for each month and for the year.

30. Average or total number of days with high winds (gales), for each month and for the year. (In the United States a " gale " is defined as a wind of 50 miles an hour or over.)

31. The average frequency of winds from the eight principal points of the compass, and the average frequency of calms, for each month and for the year. (In many localities the wind direction changes more or less regularly with the time of day. In such cases it is desirable to give the frequency of the different winds for each hour of observation.)

32. Mean monthly and annual barometric pressure, together with the mean and absolute extremes and ranges.

33. Average monthly and annual amounts of evaporation from a free water surface.

34. Statistics as to the composition and contents of the atmosphere. (Generally limited to measurements of the amount of ozone, which, as yet, " do not admit of any rigid comparisons or general conclusions " (Hann). Further data under this head have hardly found their way into climatic tables, and the methods of observation have yet to be developed.)

35. The sensations experienced by the observer, such as mild, balmy, invigorating, depressing, etc. (This subject has not yet been fully developed, but some suggestive literature exists concerning it.[1])

36. The number of cyclonic and anticyclonic areas that pass over a given locality, monthly and annually. (In many regions in middle latitudes the succession of weather types, which in the aggregate constitute climate, is largely determined by the passage of such areas, and their enumeration is essential to an adequate presentation of the climate.[2])

37. Various optical phenomena—blueness or haziness of the sky; duration of twilight; frequency of halos, coronas, rainbows, etc.

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[1] See especially J. W. Osborne, "Determination of Subjective Temperature," *Proc. Amer. Assoc. Adv. Sci.*, xxv, 1876, pp. 66–74; W. F. Tyler, "A Scheme for the Comparison of Climates," *Journal of Balneology and Climatology*, February, 1904 (also separately, London, 1904); C. Abbe, "Sensible Temperatures, or the Curve of Comfort," *Monthly Weather Review*, xxvi, 1898, pp. 362–363; W. F. Tyler, "The Psychological Aspects of Climate with a Theory Concerning Intensities of Sensation," London, 1907.

[2] See remarks by Abbe in *Smithsonian Report*, 1893, p. 491, and R. DeC. Ward, "Suggestions Concerning a More Rational Treatment of Climatology," in *Report Eighth International Geographic Congress*, 1904, Washington, 1905, pp. 277–293.

38. Average monthly and annual frequency of auroras.

39. Phenological data.

In connection with most of the above data it is desirable to give not only the average values, but also the average departures therefrom, thus exhibiting the variability of the weather from year to year.

Brief reference may here be made to the fact that the average values of the meteorological elements commonly given in climatic tables do not by any means always coincide with the values that are most likely to occur. Hence many climatologists have advocated the addition of "most frequent values" ("*Scheitelwerte*"). The extent to which such data would be useful, however, has not been fully established.[1]

In addition to the above numerical data, there are certain features of climate that can be presented only in textual descriptions, or by means of charts and diagrams. Thus the weather types, storms, and winds that are characteristic of any region must be presented verbally; the meteorological peculiarities associated with each wind direction are best shown by means of the diagrams known as "wind roses"; while the distribution of any element over a considerable area can be exhibited satisfactorily only by means of charts. Pictures have been used to a very limited extent in the presentation of climate, though they are undoubtedly of some value.[2]

Excellent examples of climatic tables, texts, charts, and diagrams will be found in Henry's *Climatology of the United States,* U. S. Weather Bureau, Bulletin Q, Washington, 1906. Among European publications, Hann's "Klimatographie von Niederösterreich," Vienna, 1904, is a model work.

Factors Controlling Climate.—LATITUDE is the most important control of climate, since it is the factor that has most to do with the geographical distribution of the insolation upon which, directly or indirectly, all meteorological processes depend. The reasons why the ultimate distribution of insolation is not wholly a question of latitude have been set forth in the chapter on temperature. The climate of any place, in so far as it depends upon the amount of insolation received by reason of latitude, is called *solar climate;* as distinguished from *telluric* or *physical climate,* which is the climate that really exists—the combined result of all the climatic factors.

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[1] The subject of "Scheitelwerte" was first brought into prominence by Hugo Meyer in his "Anleitung zur Bearbeitung meteorologischer Beobachtungen für die Klimatologie," Berlin, 1891. A *résumé* of the subject is given in Hann's "Handbook of Climatology" (Ward's translation), pp. 23–25; and illustrations of "Scheitelwerte" will be found in a number of recent climatological memoirs; e. g., the discussion of the climate of Alaska by C. Abbe, Jr., in *Professional Papers,* No. 45, of the U. S. Geological Survey, Washington, 1906.

[2] Some striking examples of photographs that bring out characteristic features of climate will be found in a paper by H. R. Mill, "Climate and the Effects of Climate," in *Quarterly Journal of the Royal Meteorological Society,* xxvii, 1901, pp. 169–184.

ALTITUDE—i. e., vertical height above sea level—has an effect upon the air temperature analogous to that of latitude. The effect of altitude upon climate is conspicuously shown in the existence of perpetual snow on the summits of high mountains, even in the hottest regions of the earth. On the other hand, the intensity of both solar and terrestrial radiation increases with increasing altitude, owing to the decreased density and greater purity of the air. Absolute humidity decreases rapidly with increasing altitude. At the highest altitudes permanently inhabited by man—about 16,000 feet—the pressure of the atmosphere is reduced to about one half of its value at sea level. Above 12,000 to 15,000 feet the rarefaction of the air has a pathological effect ("mountain sickness") upon most persons who are not acclimated; so that in such regions, at least, atmospheric pressure becomes a climatic element of importance.[1]

MOUNTAINS AND MOUNTAIN RANGES, aside from the local effects of altitude already noted, control climate by obstructing the movement of the winds and by depriving them of their moisture. Ranges running east and west often constitute sharply defined boundaries between a cold and a warm winter climate, by barring the passage of cold winds from the north or by forcing such winds to precipitate their moisture on the northern slopes and to descend the opposite slopes as warm winds (föhn). The Alps and the Himalayas are examples. Mountains have a marked effect upon the geographical distribution of rainfall. Air flowing up a mountain slope is cooled by expansion and tends to condense its water vapor; hence there is an increase in the amount of precipitation up to an altitude averaging 6,000 to 7,000 feet, in middle latitudes. Beyond this altitude the vapor content of the air is so much reduced that, despite the diminished temperature, the precipitation decreases. The increase of precipitation with altitude is beautifully shown on some of the European rainfall charts, where the stations are so close together as to bring out the local peculiarities of rainfall distribution. Such charts indicate the relief of the country very closely, the deep shading that denotes heavy rainfall also showing the location of the most important elevations. Prevailing winds, however, modify the relation of precipitation to altitude, mountains exposed to a prevailing damp wind having a wet windward and a dry leeward side.

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[1] On the physiological relations of atmospheric pressure, see Paul Bert's epoch-making work, "La pression barométrique," Paris, 1878, and the results of a recent elaborate series of investigations set forth in Zuntz, Loewy, Müller, and Caspari's "Höhenklima und Bergwanderungen in ihrer Wirkung auf den Menschen," Berlin, etc., 1906. The latter work is rich in bibliographic references.

The distance to which moist and equable air conditions extend inland is determined by the elevation of the land and its trend relative to the incident winds and the proximity of mountain ranges. The humid air from the Pacific meets the lofty range that skirts the western shore line of both North and South America; it is forced up the mountain side until at some elevation the dynamic cooling of the air by expansion causes it to precipitate its moisture mostly upon the western side of the mountain, and it passes to the interior of the continent largely bereft of that life-giving moisture which, were it not for the intervention of the mountains, would spread a mantle of luxuriant vegetation a great distance inland.

If the disintegrating effects of temperature and rainfall had worn down the Sierras, the Plateau, and the rugged crags of the Rocky Mountains to the height of the Appalachians, the vaporous atmosphere of the Pacific would flow eastward far more freely than now, and meet that which, by the convectional action of cyclones, is carried from the Atlantic Ocean and the Gulf of Mexico inland to the east slope of the Rocky Mountains; then rain would be more abundant and the whole of the United States would have arable land.

To give a further idea of the effect of mountain systems on the climates of continents one needs only to reverse the conditions just mentioned; if the Appalachian Mountains were as high as the Rocky Mountains, and if they extended farther southward and westward and bordered the Gulf of Mexico, then the Ohio River, the Mississippi, and the Missouri and their many tributaries would not exist, and the world's greatest granary would be a gray and nearly barren plain.

OCEAN CURRENTS, AND ESPECIALLY THE GULF STREAM.—Contrary to the effect on land, solar rays penetrate the sea to a considerable depth, and are quite uniformly absorbed by the stratum penetrated. In consequence a vast quantity of heat is stored by the ocean within the tropics and slowly given to the air as the ocean currents carry the warm water toward the poles.

In this connection the writer would correct what he believes to be an exaggerated popular idea relative to the effect of the Gulf Stream on the climate of Europe. The eastward extension of the Gulf Stream—generally known as the Gulf Stream Drift—doubtless brings immense quantities of relatively warm water to the shores of western Europe; but that the latter region is warmer, more humid, and less subject to radical changes in temperature than equal latitudes in North America, except on the Pacific coast, is due primarily to the mere presence of a great ocean to the westward and the prevalence of westerly winds. Without ocean currents of any description this body of water would give to the air that moves from it to Europe a mild and damp climate and a more equable temperature than is possessed by the eastern part of the North American continent.

PREVAILING WINDS distribute the effects of the other climatic factors, conveying warm air from lower to higher latitudes, cold air from higher to lower latitudes, moist air from the oceans to the lands, etc.

All regions bordering closely on the sea partake of both continental and marine climates, the predominating one being determined by the direction in which the coasts trend, their elevation, and the direction and force of the prevailing winds.

In the middle latitudes of both hemispheres the prevailing winds are from the west, and therefore continents lying in these regions have a marine climate in their western coastal regions, where the air moves from the water to the land, and nearly continental climate in their eastern coastal regions, where the general movement of the air is from the land to the sea.

THE DISTRIBUTION OF LAND AND WATER.—The climate of any place is affected by its proximity to or remoteness from bodies of water. A water surface maintains a much more uniform temperature, both from hour to hour through the day and from season to season, than a land surface; and a similar uniformity, communicated to the overlying air, constitutes the most characteristic feature of the climate over the ocean and the lands contiguous thereto. Smaller bodies of water exercise a similar influence, in a less degree, according to their size. Other effects of a water surface are a retardation of the times of occurrence of the annual maximum and minimum temperatures, and a relatively high humidity, rainfall, and degree of cloudiness. Conversely, the climates of large land surfaces are distinguished by a wide range of temperature, both diurnal and annual, and by a deficient humidity, cloudiness, and rainfall.

If the earth were all water or all land, and if the land were everywhere of the same elevation and composition, most of the factors that cause variations in climates—often considerable for regions closely contiguous—would be eliminated from the equation. Every point on the same parallel of latitude would have the same mean annual temperature, and the same average heat in summer and the same average cold in winter.

If it were all water there would be no such extremes of heat and cold as we now know, and it is probable that a thermometer exposed in the shade 4 feet from the surface of the earth would not anywhere—even at the equator—ever register above 90° F.; there would be no frost within 35° or 40° of the equator, and zero temperatures would be recorded only in regions within 30° of the poles.

If it were all land the heat would be much more intense than now in the tropics, and in the temperate and frigid zones the heat of summer and the cold of winter would reach extremes unknown at this time.

Forests.—*The soil and its covering*, according to their varied character, exercise a diversity of influences upon the air above them. (See Frosts, in Chapter VII.) Different kinds of soil, depending on their moisture and specific heat, have different thermal effects upon the overlying air. The amount of moisture in the soil affects both the temperature and the humidity of the air above. Finally, the covering of the soil—snow, grass, bushes, or trees—is a climatic factor of some importance. The influence of *forests* on climate has been the subject of much discussion, but requires still further investigation. The latest observations seem to indicate that the air within a forest differs but slightly, in mean temperature and humidity, from that of the neighboring open country.[1] Extremes of temperature, both heat and cold, are, however, slightly less over forests than over open regions. Forests appear to have but little influence on the amount of precipitation; they are the effect rather than the cause.[2]

An Equable Climate.—Within the broad confines of the United States there are many, but not all, shades and varieties of climate. One of the questions most frequently asked is: "Where shall I find a climate possessing both dryness and equability of temperature?" To this interrogatory reply must be made that the ideal climate as regards equability of temperature and absence of moisture does not exist, but that a near approach to it will be found in the southwest part of the United States.

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[1] J. Schubert, "Der Einfluss des Waldes auf das Klima nach neuen Untersuchungen der forstlichen Versuchsanstalt in Preussen," *Meteorologische Zeitschrift*, xxi, 1904, pp. 303–304. Schubert found that the mean annual temperature within a forest was only a few tenths of a degree cooler than at one or two kilometers outside the forest border, the greatest difference amounting to 1.1° C. The relative humidity may be as much as 7 per cent greater within the forest, but in spring, at noonday, it was 2 per cent less in the forest than in the open country.

[2] See J. Schubert, "Wald und Niederschlag in Schlesien," *Zeitschrift für Forst- und Jagdwesen*, xxxvii, 1905, pp. 375–380. A *résumé* of the whole subject of forests and climate will be found in U. S. Department of Agriculture, Forestry Division, *Bulletin No. 7, Forest Influences*, Washington, 1893.

The temperature of the Southwest is not equable in the sense of having an extremely small daily range, but it possesses the quality of annual uniformity in a greater degree than will generally be found elsewhere, except on the seacoast, and there the humidity is great.

The most equable temperature on the globe will be found on the high table lands and plateaus of the tropics. Bogotá, in the United States of Colombia, has an average temperature of about 59° F. for all months of the year, and the range for the entire year is less than is often experienced in a single day in some parts of the middle latitudes. But while the ideal temperature may be found on the higher elevations of the tropics, the rainfall is much greater and more continuous than in this country.

At sea level in the tropics extreme conditions of heat and moisture produce great physical discomfort. But even under the equator it is possible to escape the tropical heat of low levels by ascending from 4,000 to 6,000 feet. In the economy of nature there is a certain limit beyond which the two extremes, dryness and equability of temperature, cannot coexist; thus we may find a region so deficient in moisture as to satisfy the requirements of the case, but the very lack of moisture is a condition that facilitates radiation and thus contributes to extremes of temperature.

Regions may be found, as on the lower Nile, where there is a lack of rainfall coupled with a high and moderately uniform temperature. The mean winter temperature of Cairo, Egypt, is 56° F.; mean summer temperature, 83°; a range from winter to summer of 27°. The mean winter temperature of Phœnix, Arizona, is 52°; mean summer temperature, 87°; a range of 35°. It is, therefore, by no means difficult to find a counterpart of the far-famed Egyptian climate in the great Southwest.

While a high summer temperature is characteristic of the Southwest and other portions of the Rocky Mountain Plateau, it is a fact that the sensation of heat as experienced by animal life there is not accurately measured by the ordinary thermometer. The sensation of temperature which we usually refer to the condition of the atmosphere depends not only on the temperature of the air, but also on its dryness and the velocity of the wind. The human body, when perspiring, freely evaporates the moisture of its surface to the air in the arid regions, and this lowering of its temperature prevents sunstrokes, which, in the more humid regions from the Mississippi valley eastward, occur in great number with the air temperature much less than obtains in the West.

The meteorological instrument that registers the temperature of evaporation, and thus in some measure the actual heat felt by the human body, is the wet-bulb thermometer. The latter, as indicated by its name, is simply an ordinary mercurial thermometer whose bulb is wetted with water at the time of observation.

Effect of Climate on the Races.—Climate is the most potent of all factors in the environment of races. It is climate and soil, plus heredity and form of government, that produce either vigorous or weak peoples. The anticyclonic systems of air that constitute cold waves have a marked downward component of motion. This motion brings from a considerable altitude to the surface of the earth ozone and high electrical potential, which are strongly stimulating to man and to other forms of animal life. These cold north winds have a much greater specific gravity than warm and humid winds, and owing to this condition, added to the force with which they come, scatter and diffuse the befouled air near the surface of the earth. Enough has been said to indicate that climate is nearly as important a part of the environment of the animal life as it is of the vegetable existence, and that a cold climate, if it be not so extreme as to limit the production of cereal crops, favors the development of strong races of men.

Classification of Climates.—Climates are variously classified, with reference to (1) their controlling factors, as latitude (tropical, temperate, and polar climates), distribution of land and water (continental and marine climates); or (2) the meteorological elements, as temperature (hot and cold climates), moisture (damp and dry climates); or (3) their effects on living beings, as relaxing, invigorating, etc. The following table, by Dr. W. F. R. Phillips,[1] exhibits the classifications that are in common use and indicates the basis of each:

CLASSIFICATION BASIS.	Subdivisions Under Classification.	General Characteristics of Each Subdivision.
Solar or astronomical.	Tropical............	Usually mild, equable, moist, warm, average temperature 80° F. Rainfall frequent and heavy over water and over windward land exposures. Nights usually clear, afternoons cloudy. No general storms. Seasons, rainy and dry; but this division is only a relative one.

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[1] A. H. Buck, "Reference Handbook of the Medical Sciences," new ed., New York, 1901, *s. v.* "Climate."

Classification Basis.	Subdivisions Under Classification.	General Characteristics of Each Subdivision.
Solar or astronomical.	Temperate	Unsettled weather, great and variable changes in temperature, rainfall, and moisture from season to season and day to day. Region of cyclonic storms, cold and hot waves. floods and droughts.
	Arctic	Cold; temperature on average considerably below freezing. Scanty rainfall. Very short but hot summer. Winter long and severe. Storms infrequent.
Geographical.	Continental	High temperature in daytime, low at night. Difference between day and night temperatures increases toward center of continent. Great variations in temperature, sometimes hot, sometimes cold. Moisture variable from almost saturation to aridity. Rainfall subject to great variations and extremes. General tendency to extremes in all climatic elements.
	Oceanic	Temperature equable; range between day and night hardly exceeds 2° to 4° F. in mid-ocean. Moisture high but constant. Rainfall frequent.
	Insular and littoral	Intermediate between above, partaking more or less of the characteristics of one or the other.
Topographical (land).	Plain	Extremes of temperature great, rainfall uncertain, humidity low.
	Hill	Extremes of temperature less than plain, rainfall greater, humidity higher.
	Mountain	Generally same as hill, except effects of altitude become more evident; rainfall increases up to about 5,000 feet, then decreases.
	Valley	Extremes of temperature greater than hill. Humidity greater; rainfall greater than plain.
	Desert	Rainless; great extremes of temperature between night and day and season and season.
	Artificial	Such as climates of large cities. Temperature of cities always higher than surrounding country; haze and cloud and fog more frequent.
Aërophysical.	Temperature	Hot Intermediate Cold According to the degree of heat adopted as the standard of comparison.
	Humidity	Damp or moist Intermediate Dry or arid According to standard of humidity adopted.
Physiological.	Invigorating Relaxing Rigorous, etc	According to the general effects of the particular climate.
	Mild Pleasant Humid Disagreeable, etc	According to the general sensation produced, etc.

Classification with Respect to Rainfall.—With an annual rainfall of less than 18 inches agriculture can hardly be carried on successfully without irrigation, while a region with less than 10 inches is a desert. A convenient classification of the annual rainfall, with reference to its biological effects, is the following, adapted from Waldo[1]:

Excessive rainfall, over 75 inches.
Copious rainfall, 50–75 inches.
Moderate rainfall, 25–50 inches.
Light rainfall, 10–25 inches.
Desert rainfall, under 10 inches.

The distribution of rainfall throughout the year is a no less important feature of the climate than the annual amount. Köppen has published a chart of the hyetal regions of the world, based on the seasonal distribution of rain frequency, amount of rainfall, and cloudiness.[2]

Classifications with Respect to the Distribution of Plants and Animals.—Köppen has also proposed an ingenious classification of climatic types as expressed by characteristic forms of vegetal and animal life.[3] Twenty-four types are distinguished, each characterized by a flora or fauna requiring a certain annual amount and seasonal distribution of temperature and moisture. The types are generally named after a representative plant or animal, as " Liana Climate," " Baobab Climate," " Birch Climate," " Yak Climate," " Penguin Climate "; or after some characteristic meteorological phenomenon, as " Simoom Climate," " Buran Climate," etc.

While the laws governing the relations of climate to the distribution of animal and plant life have not been fully worked out, nevertheless the empirical delimitation of life areas or zones, and the determination of their characteristic climatic conditions, is one of the most fruitful processes of applied climatology. Valuable work along this line has been done by the U. S. Biological Survey. The Survey spent years in mapping the principal life zones and their subdivisions in the United States, and in connecting each with the climatic data gathered by the Weather Bureau.

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[1] F. Waldo, "Elementary Meteorology," New York, 1896, pp. 148, 150.

[2] Reproduced in Bartholomew's "Physical Atlas," vol. iii, Edinburgh, 1899, Plate 19.

[3] W. Köppen, "Versuch einer Klassifikation der Klimate, vorzugsweise nach ihren Beziehungen zur Pflanzenwelt," Leipzig, 1901.

From " life zones " it was an easy transition to " crop zones "; the climatic requirements of the several species and varieties of cultivated plants were brought to light, and the crops appropriate to each region of the United States were thus determined. The information thus acquired has resulted in the saving of large sums of money that would otherwise have been spent in attempts to make crops grow in regions totally unfitted for their cultivation; and, on the other hand, it has encouraged farmers to introduce suitable plants not previously cultivated in their vicinity.[1]

An extension of the same idea is seen in the work of introducing plants from foreign lands, carried on by the United States Bureau of Plant Industry. Before attempting to introduce a foreign plant the climatic conditions of its original habitat are ascertained as fully as possible, and a region of the United States having a similar climate is chosen for its cultivation. The only limit to the successful application of this process, at present, is due to the dearth of climatic statistics for many regions of the earth.[2]

The factors necessary to the development of plant life are light, heat, soil, and moisture. The ideal conditions as regards these essentials do not usually obtain, or, if they do, multitudes of plants seek to take possession of the region, so that there is a continuous struggle for existence in which many more plants fail than succeed.

The climatic factors, heat and moisture, are combined in several ways in different parts of the globe, and these combinations give widely different vegetation; thus a maximum of heat and a minimum of water give desert conditions where only specially adapted plants can exist. If, on the other hand, a maximum of heat is combined with a maximum of water, the result will be vegetation such as exists only in the rainy tropics. The possible combinations of the two climatic factors are very numerous, as are also those of soil and the effects of animal life and human agencies. Yet the vegetation of the globe is susceptible of a fairly definite classification. Following Humboldt, and adopting such terms as express in a general manner the vegetation characteristic of each zone, we have the following classification:

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[1] See C. H. Merriam, "Life Zones and Crop Zones of the United States," Washington, 1898, U. S. Department of Agriculture, Division of Biological Survey, *Bulletin 10.*

[2] A digest of the principal literature on the relations between climates and crops, so far as published down to 1891, will be found in Abbe's "First Report on the Relations Between Climates and Crops," Washington, 1905, U. S. Weather Bureau, *Bulletin 36.*

Zones of—	Average Temperature.
1. Palms and bananas	78°-82°
2. Tree ferns and figs	73°-78°
3. Myrtles and laurels	68°-73°
4. Evergreens	60°-68°
5. Deciduous trees	48°-60°
6. Conifers	40°-48°
7. Lichens, saxifrages, and dwarf shrubs	32°-40°
8. Lichens and mosses	32° and below.

While in a general way these zones stretch around the world in wavy belts, somewhat as do the isotherms, similar belts may be found encircling mountain peaks and chains with increasing altitude above sea level. Indeed, it is possible to pass successively from tropic to arctic vegetation on a single mountain peak in the tropics.

That changes in the climate of the earth have left a marked impress upon the fauna of the globe there can be no doubt. The great northern ice sheet and the accompanying cold of the glacial period, if it did not cause the extermination of the receding fauna, led to its migration to more congenial climates.

The part played in the faunal distribution of the globe by the present climate seems to be indirect rather than direct, although there are many facts which seem to point to a direct relation. While it is true that the fur-bearing animals of the frozen north are generally to be found in arctic regions, yet they send their representatives far into the temperate latitudes, and indeed into the borders of the regions inhabited by the more exclusively tropical species. On the other hand, the tiger, whose home is naturally associated with the hot districts of India and the Indian Archipelago, is equally at home in the elevated regions of the Caucasus and the Himalayas, where his footprints are not infrequently found impressed in fields of snow. Other groups of animals are more limited in their migrations. Some are so closely adapted to an arboreal life that they never stray far beyond the limits of forest vegetation, while others are so tolerant of climatic change that the limit of their possible range is conditioned only by the character and quantity of the food supply and the interposition of impassable physical barriers.

Climatic Zones and Provinces.—For the purposes of comparative climatology it is convenient to divide the earth's surface into natural regions with respect to climate, though it is recognized that the boundaries of such regions are usually more or less arbitrary.

Thus we have, first of all, a division into temperature zones, which are popularly identified with the astronomical zones bounded by the tropics and the polar circles, and are five in number—viz., the Torrid Zone, the North and South Temperate Zones, and the Arctic and Antarctic Zones. The zones, as thus bounded, correspond exactly with the distribution of solar climate, but only very roughly with that of physical climate, since the isotherms do not run parallel with the latitude circles. Hence several writers have endeavored to readjust the zones in accordance with actual conditions. Thus it has been proposed by Supan to limit the zones, for climatological purposes, by isotherms instead of parallels of latitude, as shown on Chart 36. The limiting isotherms were chosen with reference to the growth of important classes of plants; the annual isotherm of 68° F. coinciding approximately with the poleward limit of palms, and the isotherm of 50° F. for the warmest month being coincident with the poleward limit of forest trees and cereals. An arrangement proposed by Köppen takes account not only of the mean temperatures, but also of the duration of the hot, temperate, and cold seasons.[1] Prof. William M. Davis has proposed to define the zones by the prevailing wind systems, including the whole area of the trade belts within the torrid zone, and limiting the temperate zones to the regions of the prevailing westerlies. However, the simple classification of the zones first mentioned above, based upon the geometrical distribution of sunshine, with limits sharply defined by the tropical and polar circles, is the most convenient for the purposes of elementary description, and is the only one in general use.

In discussing the climate of any large area it is frequently convenient to establish subdivisions of the area having more or less homogeneous climatic features within their limits, which may then be treated as climatic units and discussed separately. Such subdivisions are often called *climatic provinces*. These climatic subdivisions of a country are adapted to serve as forecast districts, since the factors that determine a homogeneous climate tend also to produce homogeneous weather.

A. Supan has proposed a division of the whole surface of the globe into thirty-five climatic provinces, based principally upon temperature and rainfall, but partly, also, upon winds and orographical conditions.[1] (See Chart 37.)

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[1] W. Köppen, "Die Wärmezonen der Erde," etc., *Meteorologische Zeitschrift*, i, 1884, pp. 215–226. Köppen's chart is reproduced in Waldo's "Elementary Meteorology," New York, 1896, pp. 304–305.

CHANGES OF CLIMATE.—There is abundant evidence that great changes took place in the climate of the earth during the prehistoric ages of which geology furnishes the record. Fossil remains show that regions now covered with perpetual ice once supported a luxuriant flora and fauna; many regions in the temperate and equatorial zones that are now deserts were once overgrown with forests; a great Glacial Period (probably the latest of a series of such periods) during Pleistocene times pushed the arctic ice-cap far to the south of its present limits, and caused the snow lines of European and North American mountains to descend thousands of feet below their present levels. Many attempts have been made to trace the fluctuations of geological climates and to determine their causes. Variations in the obliquity of the ecliptic, in the amount of carbon dioxide and water vapor in the atmosphere, and in the output of radiant energy from the sun, are among the causes that have been invoked by the numerous investigators of this subject.[2]

It is probable that appreciable change of climate has not occurred within historic time. That a gradual desiccation of extensive regions—marked by the shrinking or the disappearing of lakes and inland seas, and the encroachment of deserts upon contiguous cultivated areas—has been going on for centuries in many parts of the world appears to be well established; but it is becoming clear that this process is only one phase of a long-period oscillation that must be measured in a unit of geologic time.

Exact meteorological observations are of too recent a date to shed any light upon the question of secular variations of climate—i. e., variations persisting in one direction for several centuries. Evidence is accumulating, however, to prove the existence of more or less regular oscillations of the meteorological elements in periods brief enough to be discernible in the records of such observations, but also of very small amplitude compared with the long-period fluctuations of geologic times.

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[1] The original description of these provinces appears in Supan's "Grundzüge der physischen Erdkunde." An English translation will be found in Bartholomew's "Physical Atlas," vol. iii, Edinburgh, 1899, pp. 7–8.

[2] For a bibliography of the whole subject of changes of climate see Supan, "Grundzüge der physischen Erdkunde," 4th ed., Leipzig, 1908, pp. 251–253. Consult further the numerous references in Hann's "Handbuch der Klimatologie," 3d ed., I. Band, p. 345 *et seq.*

The study of the question of short-period oscillations has been approached from two sides. A large number of investigators, setting out from the well-known eleven-year sunspot period, which shows so clearly a relation to the phenomena of terrestrial magnetism, have endeavored to find a similar parallelism in the march of the meteorological elements. The results have been so conflicting that it is impossible to summarize them briefly. While a fluctuation of certain elements coinciding with the sunspot period appears to have been made out for many stations and regions, it is difficult to coördinate the results so far attained so as to show how the periodicity of the sunspots is related to the weather of the earth as a whole. Sir Norman Lockyer and Bigelow have suggested that the study of solar prominences will probably shed more light upon the control of terrestrial weather by the sun than the study of sunspots.

A more fruitful method of investigation has been that of examining the meteorological records in the first instance for evidences of periodicity, without regard to cosmical or other periods previously established. The application of this method has caused Ed. Brückner[1] to believe in the existence of a thirty-five-year period in the fluctuations of temperature and rainfall. He finds (see Table XXXI) that groups of relatively cool and rainy years alternate with groups of warmer and dryer years, the whole cycle having an *average* period of thirty-five years, though the actual length of any individual cycle may be as great as fifty years or as little as twenty. The average amplitude of the fluctuations for the earth as a whole is only about 1° C. for temperature and 12 per cent for rainfall; but the fluctuations are more marked in the interior of continents than on the coasts; they may be extensive enough in some parts of the world to have a bearing upon agriculture. Brückner has traced the effects of the thirty-five-year oscillations upon crops and the prices of grain.[2]

Dr. W. J. S. Lockyer (son of Sir Norman Lockyer) has endeavored to show that there is a corresponding thirty-five-year period in the solar activity, denoted by the variation in the total spotted area, and in the epoch of the sunspot maxima with respect to the minima.[3]

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[1] E. Brückner, "Klimaschwankungen seit 1700, nebst Bemerkungen über der Diluvialzeit," Vienna, 1890.

[2] E. Brückner, "Der Einfluss der Klimaschwankungen auf die Ernteerträge und Getreidepreise in Europa," *Geographische Zeitschrift*, i, 1895, pp. 39–51, 100–108.

[3] W. J. S. Lockyer, "The Solar Activity 1833–1900," *Proceedings Royal Society of London*, lxviii, 1901, pp. 285–300.

TABLE XXXI.

Oscillations of Climate According to Brückner.
(*Supan, "Grundzüge der physischen Erdkunde."*)

YEARS.	Temperature. ° C.	Rain. (Per Cent.)	Lakes.	Beginning of Alpine Glacier Movement.
1731–1735	−0.34	−4		1735 advance
1736–1740	−0.43*	+9	1740 Max.	
1741–1745	−0.35	−6*		
1746–1750	**+0.45**	+5		1750 retreat
1751–1755	+0.16	+5		
1756–1760	−0.08	−3	1760 Min.	
1761–1765	−0.10	+0		
1766–1770	−0.42*	−4*		1767 advance
1771–1775	+0.24	+7		
1776–1780	+0.15	−2	1780 Max.	
1781–1785	+0.18	−2		
1786–1790	−0.11	+2		
1791–1795	**+0.46**	−2		
1796–1800	+0.07	−1	1800 Min.	1800 retreat
1801–1805	+0.26	−4*		
1806–1810	−0.18	+3		
1811–1815	−0.46*	+0		1814 advance
1816–1820	−0.35	+0	1820 Max.	
1821–1825	**+0.56**	−2		1823 retreat
1826–1830	+0.14	−0		
1831–1835	+0.03	−8*	1835 Min.	
1836–1840	−0.39*	−5		1840 advance
1841–1845	−0.00	+1		
1846–1850	−0.08	+3	1850 Max.	
1851–1855	**+0.11**	+1		
1856–1860	+0.06	−4		1856 retreat
1861–1865	−0.06	−5*	1865 Min.	
1866–1870	+0.11	−1		
1871–1875	−0.04	+2		1875 advance
1876–1880	−0.07	+7	1880 Max.	
1881–1885	−0.08*	+6		

Means for the earth as a whole: the positive and negative values represent variations in the mean temperature and the annual rainfall respectively, in the latter case in percentages of the mean annual amounts. Minima are denoted by an asterisk: maxima by full-face type.

Climate of the United States.—Reference to Chart 37 will show that the vast territory of the United States falls within several of Supan's " climatic provinces "—viz., Northwest American Coastal Province, with a mild, equable, rainy climate (including the rainiest region in the United States); Californian Province, which is relatively cool, especially in summer, and has a marked subtropical rainy season; North American Mountain and Plateau Province, dry and subject to great yearly and daily ranges of temperature; Hudson (North Canadian) Province, likewise relatively dry and subject to great extremes of temperature; Atlantic (East North American) Province, with a variable climate, largely under cyclonic control, rainfall well distributed through the year, and wide range of temperature even on the coast; and the West Indian Province, which includes Florida and the Gulf coast, with equable temperature and rain at all seasons, but with a marked summer maximum.

Applying what has been said above regarding the factors controlling climate we find that the United States lies wholly within the North Temperate Zone, whence it has a temperate solar climate; it lies in the region of prevailing westerly winds, whence an equable climate of oceanic character prevails on its westward coast; and it is traversed from north to south by a lofty mountain system comparatively near the western coast, whence the climate of that coast does not extend far inward, but gives place, east of the mountain barrier, to a typical continental climate, which prevails over much the greater part of the United States. The climate of the eastern seaboard is somewhat tempered by the proximity of the Atlantic Ocean, though in a far less degree than is the western coast by that of the Pacific, on account of the prevailing direction of the wind.

A most important influence upon the climate of the greater part of the United States, especially upon the northern part of the region east of the Rocky Mountains, is the succession of cyclonic and anticyclonic disturbances that continually sweep across the country from west to east, bringing rapidly alternating periods of heat and cold, rainy weather and clear skies. This cyclonic control of climate is not apparent from the ordinary climatic charts, which show the average distribution of the meteorological elements, but should never be lost sight of in discussing the climate of the United States, in which the cyclonic element is extremely pronounced.

Charts 38 to 45 and Table XXXII present a few of the most important features of the climate of the United States. For more complete information on this subject the student should consult Prof. A. J. Henry's "Climatology of the United States" (Washington, 1906) and some of the other works named on page 282.

Table XXXII.

Absolute Maximum and Minimum Temperatures for Selected Stations, 1871–1908.

Station.	Max. °F.	Min. °F.
New England and Middle Atlantic States.		
Eastport	93	−21
Portland	98	−17
Boston	102	−13
Block Island	89	−4
New Haven	100	−14
Buffalo	95	−14
Rochester	99	−14
Oswego	100	−23
Albany	100	−24
New York City	100	−6
Erie	94	−16
Pittsburg	103	−20
Philadelphia	103	−6
Atlantic City	99	−7
Baltimore	104	−7
Washington	104	−15
Lynchburg	102	−6
Norfolk	102	2
South Atlantic and East Gulf States.		
Charlotte	102	−5
Wilmington	103	5
Charleston	104	7
Atlanta	100	−8
Augusta	105	3
Jacksonville	104	10
Key West	100	41
Pensacola	103	7
Montgomery	107	−5
Mobile	102	−1
Vicksburg	101	−1
West Gulf States and Southern Rocky Mountain Slope.		
Little Rock	106	−12
Shreveport	107	−5
New Orleans	102	7
Palestine	104	−6
El Paso	113	−5
San Antonio	108	4
Galveston	98	8
North Central District.		
Bismarck	106	−44
Moorhead	102	−48
St. Paul	104	−41
North Central District.—Continued.		
Marquette	108	−27
Alpena	98	−27
Detroit	101	−24
Milwaukee	100	−25
La Crosse	104	−43
Huron	108	−43
North Platte	107	−35
Omaha	106	−32
Des Moines	109	−30
Davenport	106	−27
Keokuk	108	−24
Dodge City	108	−26
St. Louis	107	−22
Chicago	103	−23
Springfield, Ill.	107	−24
Cairo	106	−16
Indianapolis	106	−25
Toledo	102	−16
Cleveland	99	−17
Columbus	104	−20
Cincinnati	105	−17
Louisville	107	−20
Knoxville	100	−16
Nashville	104	−13
Memphis	104	−9
Chattanooga	101	−10
Rocky Mountain and Plateau Region.		
Boise	111	−28
Helena	103	−42
Cheyenne	100	−38
Denver	105	−29
Santa Fé	97	−13
Winnemucca	104	−28
Salt Lake City	102	−20
Yuma	118	22
Pacific Coast States.		
Spokane	104	−30
Portland	102	−2
Roseburg	104	−6
San Francisco	100	29
San Diego	101	32
Red Bluff	115	18
Los Angeles	109	28

BIBLIOGRAPHY

On climate in general the chief authority is J. HANN'S "Handbuch der Klimatologie," 3d ed., vol. i, Stuttgart, 1908. An English translation of the second edition, with additions, has been made by R. DeC. Ward, New York, 1903. A companion volume, on the human relations of climate, is R. DEC. WARD'S "Climate, Considered Especially in Relation to Man," New York, 1908.

On climatography—i.e., the description of particular climates—the principal reference book applying to the earth as a whole is HANN'S "Handbuch der Klimatologie," vols. ii and iii. There is no English translation. The chief collection of climatic charts for the world at large is J. G. BARTHOLOMEW and A. J. HEBBERTSON'S beautiful "Atlas of Meteorology," constituting vol. iii of BARTHOLOMEW'S "Physical Atlas," Westminster, 1899. Rainfall statistics for all extra-European countries are collected in ALEXANDER SUPAN'S "Die Verteilung des Niederschlags auf den festen Erdoberfläche," Gotha, 1898.

Discussions of the climate of particular countries and regions are exceedingly numerous. The following are a few of the most important:

RUSSIA, OBSERVATOIRE PHYSIQUE CENTRAL NICOLAS, "Atlas climatologique de l'empire de Russie," St. Pétersbourg, 1900. *Same.* Notice explicative. St. Pétersbourg, 1900.

HELLMANN, G., "Die Niederschläge in den norddeutschen Stromgebieten," Berlin, 1906. 3 vols.

THIELE, PAUL, "Deutschlands landwirtschaftliche Klimatographie," Bonn, 1895.

GREAT BRITAIN, METEOROLOGICAL OFFICE, "Rainfall Tables of the British Islands, 1866–90," London, 1897.

ROYAL MEDICAL AND CHIRURGICAL SOCIETY OF LONDON, "The Climates and Baths of Great Britain," London, etc., 1895–1902. 2 vols.

[NAKAMURA, K.], "The Climate of Japan," Tokio, 1893. (Japan, Central Meteorological Observatory.)

ELIOT, SIR JOHN, "Climatological Atlas of India," Edinburgh, 1906. (India, Meteorological Department.)

ALGUÉ, JOSÉ, "The Climate of the Philippines," Washington, 1904. (United States Bureau of the Census, Census of the Philippine Islands, 1903, *Bulletin 2*.)

Saderra Maso, Miguel, "The Rainfall in the Philippines," Manila, 1907. (Philippine Islands, Weather Bureau.)

Abbe, Cleveland, Jr., "The Climate of Alaska," Washington, 1906. (Extract from *Professional Paper No. 45,* U. S. Geological Survey.)

Bigelow, Frank Hagar, "The Daily Normal Temperature and the Daily Normal Precipitation of the United States," Washington, 1908. (United States Weather Bureau, *Bulletin R.*)

Blodget, Lorin, "Climatology of the United States, and of the Temperate Latitudes of the North American Continent," Philadelphia, 1857.

Henry, Alfred Judson, "Climatology of the United States," Washington, 1906. (United States Weather Bureau, *Bulletin Q.*)

Henry, Alfred J., "Rainfall of the United States, with Annual, Seasonal, and Other Charts," Washington, 1897. (United States Weather Bureau, *Bulletin D.*)

United States Weather Bureau, "Climatic Charts of the United States," 2d ed., Washington, 1904. (W. B. No. 301.)

McAdie, Alexander G., "Climatology of California," Washington, 1903. (United States Weather Bureau, *Bulletin L.*)

Voss, Ernst Ludwig, "Die Niederschlagsverhältnisse von Südamerika," Gotha, 1907. (Petermanns Mitteilungen, Ergänzungsheft No. 157.)

Davis, Walter G., "Climate of the Argentine Republic, Compiled from Observations made to the End of the Year 1900," Buenos Aires, 1902. (Argentine Republic. Ministerio de agricultura.)

APPENDIX

Brief Tables of Equivalents

Length.

1 millimeter = 0.0393700 inch.[1]
1 centimeter = 0.393700 inch.
1 decimeter = 3.93700 inches.
1 meter = 39.3700 inches.
1 kilometer = 39370.0 inches. = 0.621370 mile.

Mass.

1 milligram = 0.015432356 grain.
1 centigram = 0.15432356 grain.
1 decigram = 1.5432356 grains.
1 gram = 15.432356 grains.
1 kilogram = 15432.356 grains. = 2.204621 lbs. avoirdupois.

Temperature.

−100° C. = −148° F.
−95° C. = −139° F.
−90° C. = −130° F.
−85° C. = −121° F.
−80° C. = −112° F.
−75° C. = −103° F.
−70° C. = −94° F.
−65° C. = −85° F.
−60° C. = −76° F.
−55° C. = −67° F.
−50° C. = −58° F.
−45° C. = −49° F.
−40° C. = −40° F.
−35° C. = −31° F.
−30° C. = −22° F.
−25° C. = −13° F.
−20° C. = −4° F.
−15° C. = 5° F.
−10° C. = 14° F.
−5° C. = 23° F.
0° C. = 32° F.
5° C. = 41° F.
10° C. = 50° F.
15° C. = 59° F.
20° C. = 68° F.
25° C. = 77° F.
30° C. = 86° F.
35° C. = 95° F.
40° C. = 104° F.
45° C. = 113° F.
50° C. = 122° F.
55° C. = 131° F.
60° C. = 140° F.
65° C. = 149° F.
70° C. = 158° F.
75° C. = 167° F.
80° C. = 176° F.
85° C. = 185° F.
90° C. = 194° F.
95° C. = 203° F.
100° C. = 212° F.

The temperature of freezing water is marked 0 on the Centigrade and 32 on the Fahrenheit scale, while that of boiling water at atmospheric pressure is marked 100 and 212, respectively. That is, on the Centigrade scale there are 100 equal divisions or steps between these two fixed temperatures, while on the Fahrenheit there are 180. Hence the change of 100°

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[1] The legal equivalent in the United States. In Great Britain it is 0.03937079 inch.

C. from any given temperature is the same as a change of 180° F. in the same direction from the same temperature. Or, reduced to the lowest whole numbers, a change of 5° C. is equivalent to a change of 9° F. But, as explained, when the Centigrade scale reads 0° the Fahrenheit scale reads 32°. Evidently, therefore, conversion from the one scale to the other is correctly effected by substitution in either of the following formulæ:

$$C^\circ = \tfrac{5}{9}\,(F - 32),$$

$$\text{or } F^\circ = \tfrac{9}{5}\,C + 32.$$

CHARTS

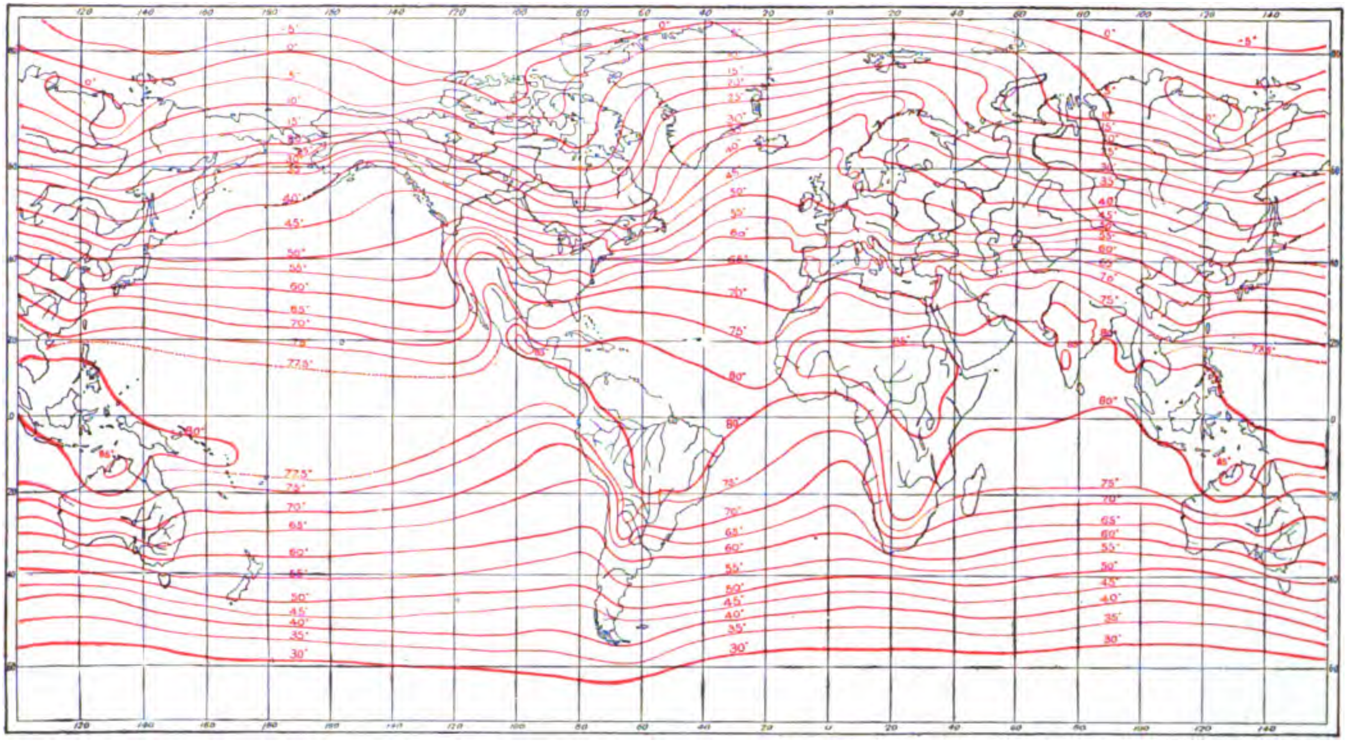


CHART 1.—MEAN ANNUAL ISOTHERMS (Buchan).

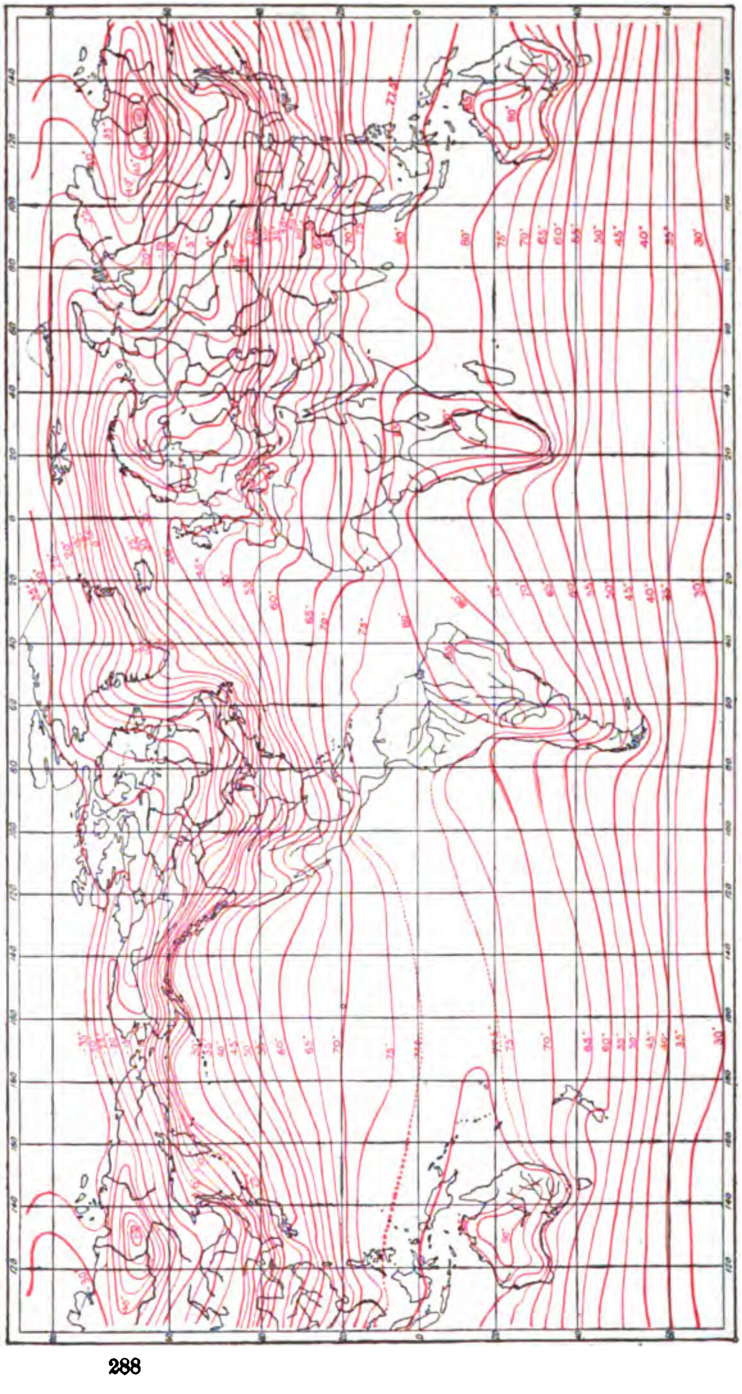


CHART 2.—JANUARY ISOTHERMS (Buchan).

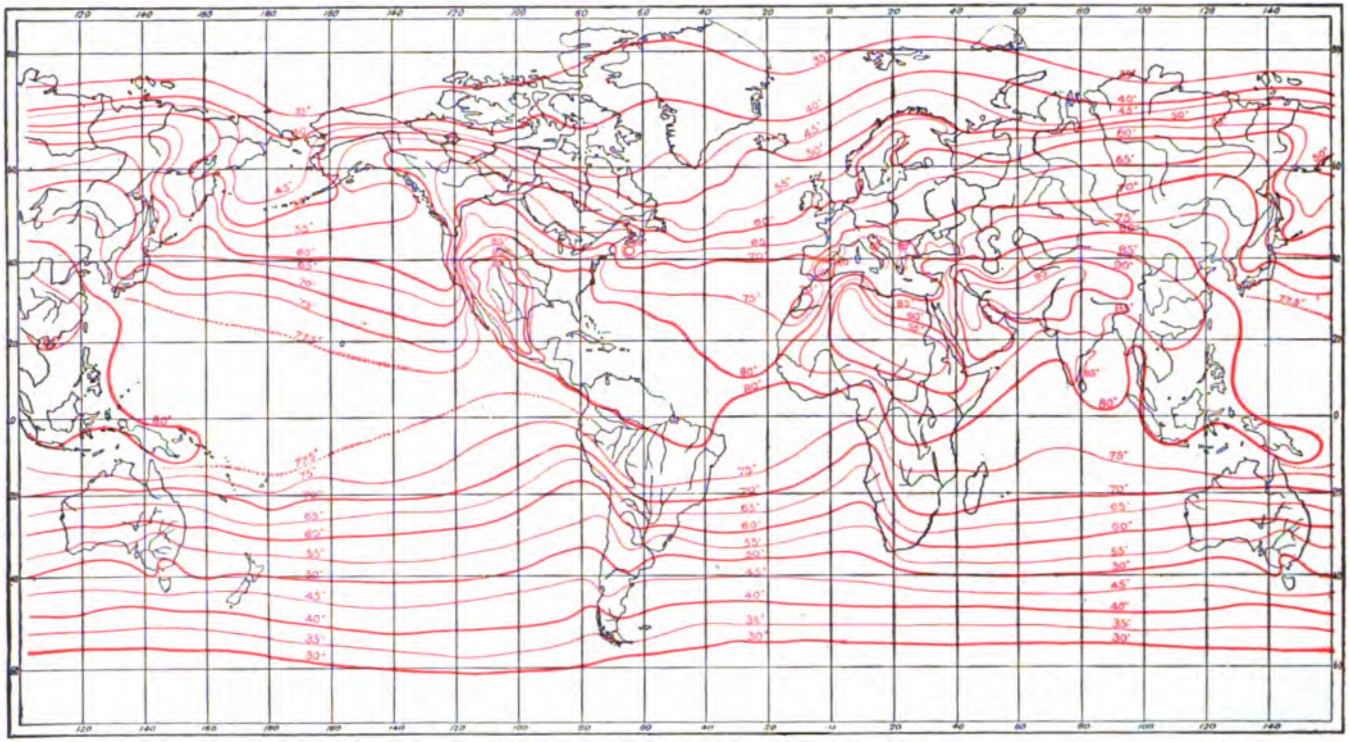


CHART 3.—JULY ISOTHERMS (Buchan).

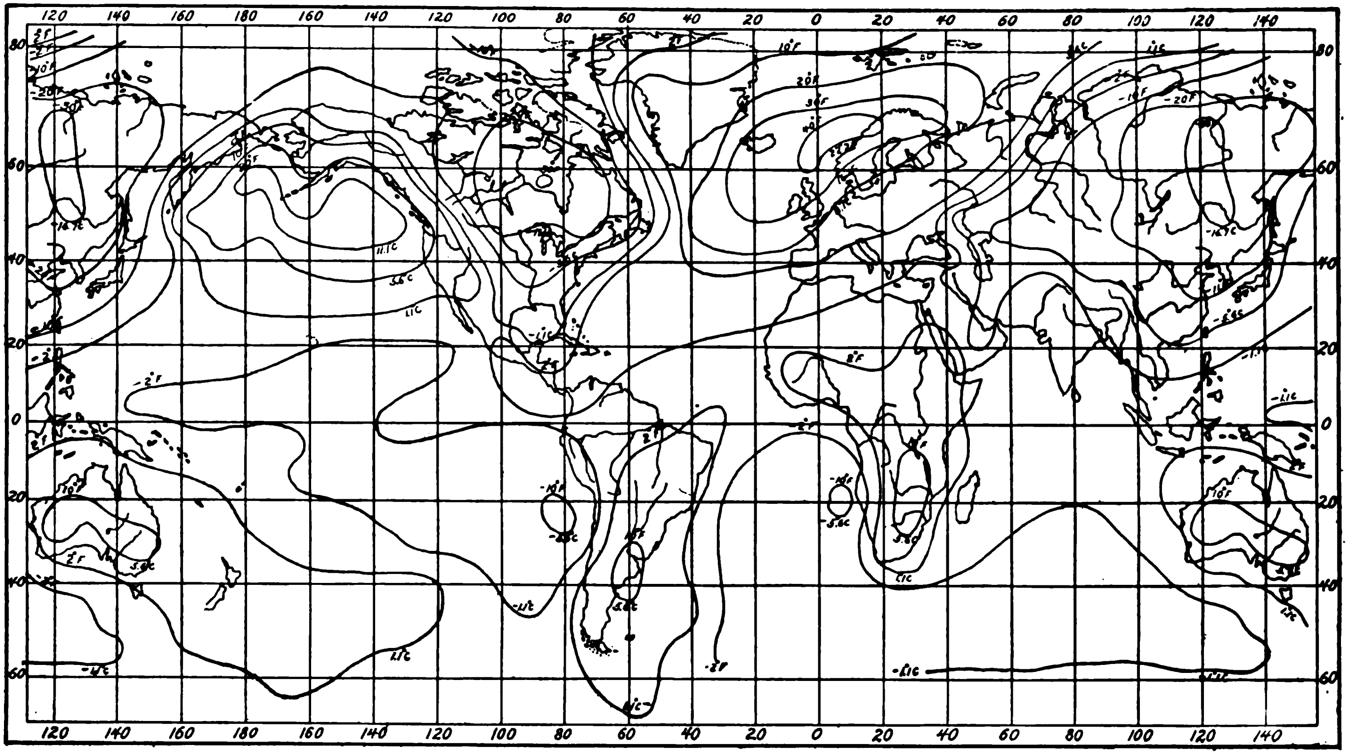


CHART 4.—ISANOMALOUS LINES FOR JANUARY (Batchelder).

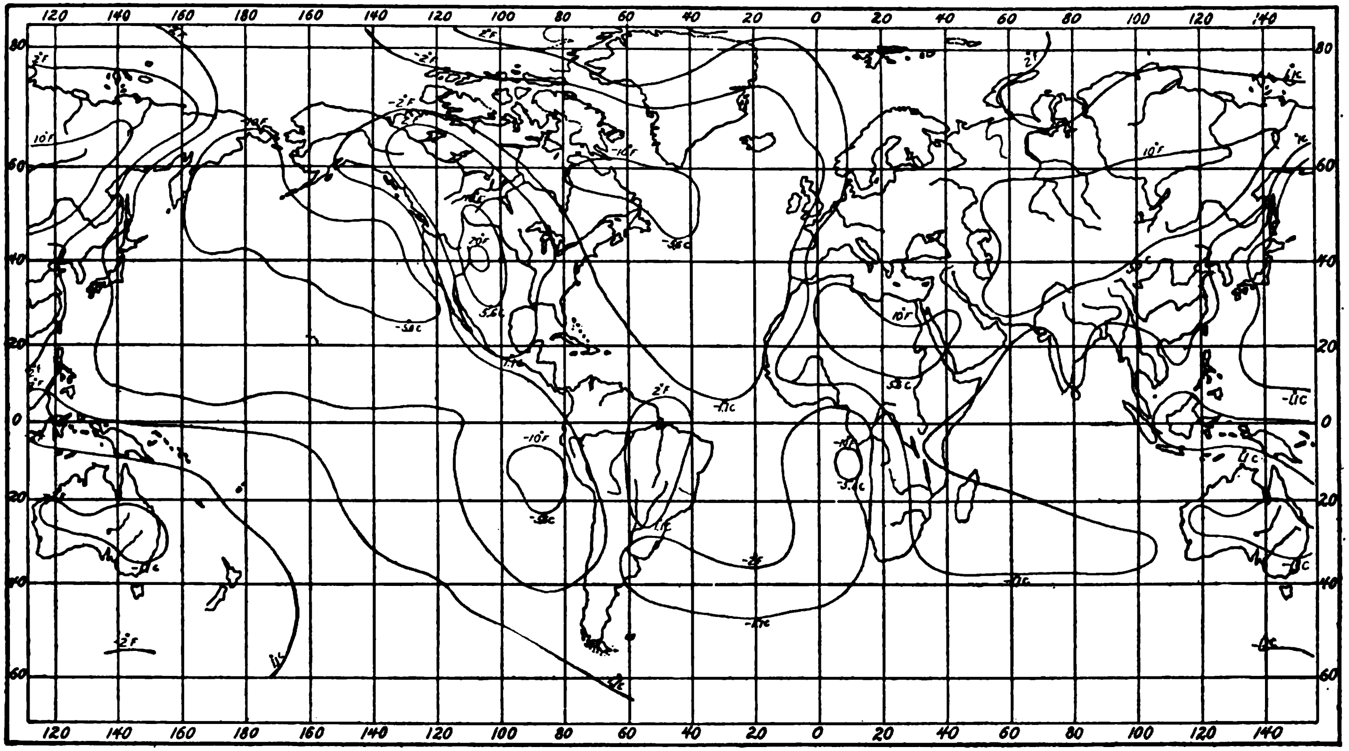


CHART 5.—ISANOMALOUS LINES FOR JULY (Batchelder).

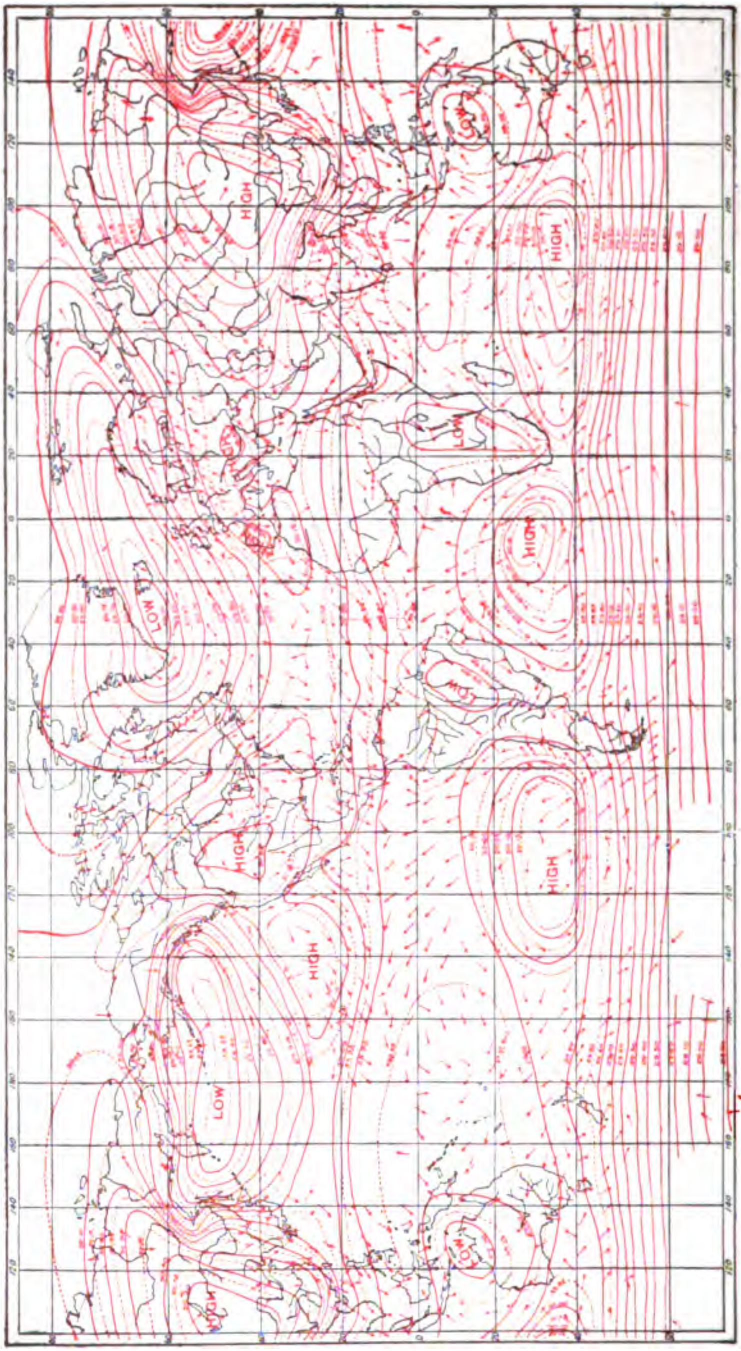


CHART 6.—HIGH AND LOW CENTERS OF ACTION AND PREVAILING WINDS OF THE GLOBE FOR JANUARY (Buchan).

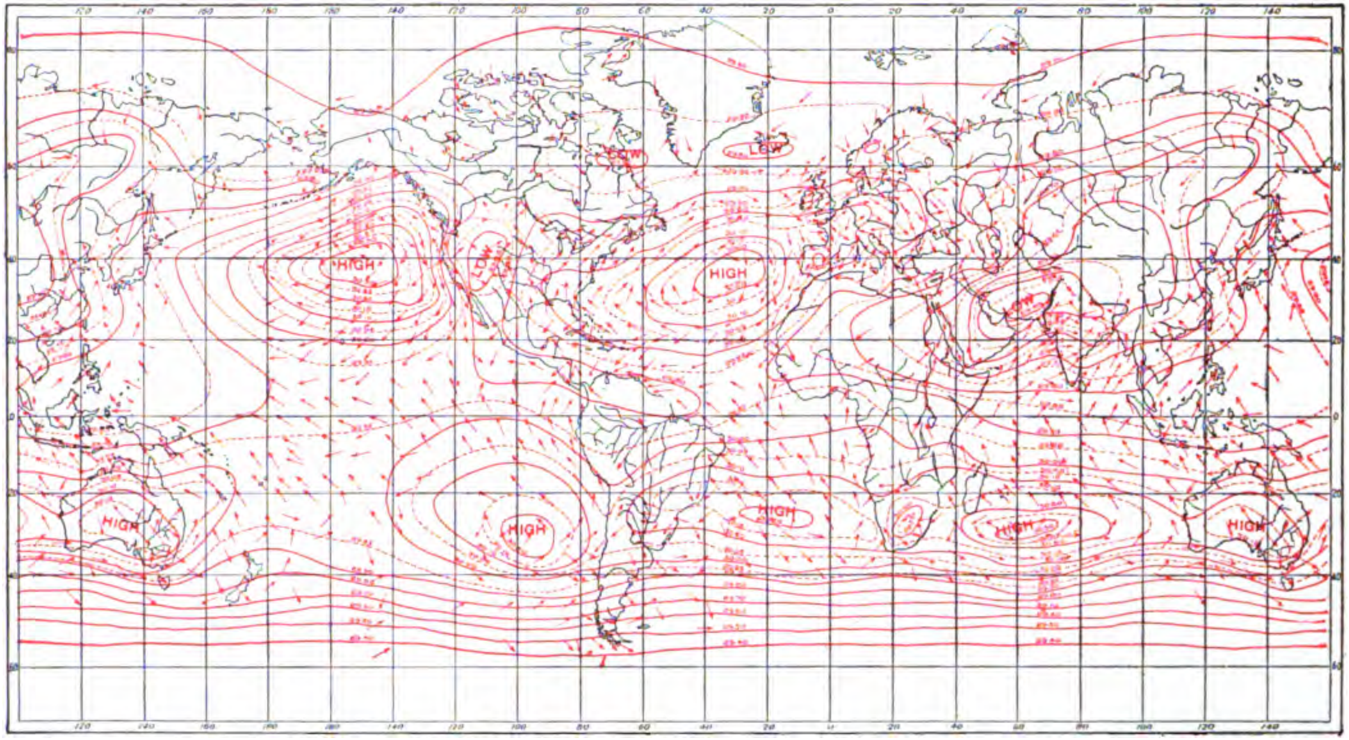


Chart 7.—High and Low Centers of Action and Prevailing Winds of the Globe for July (Buchan).

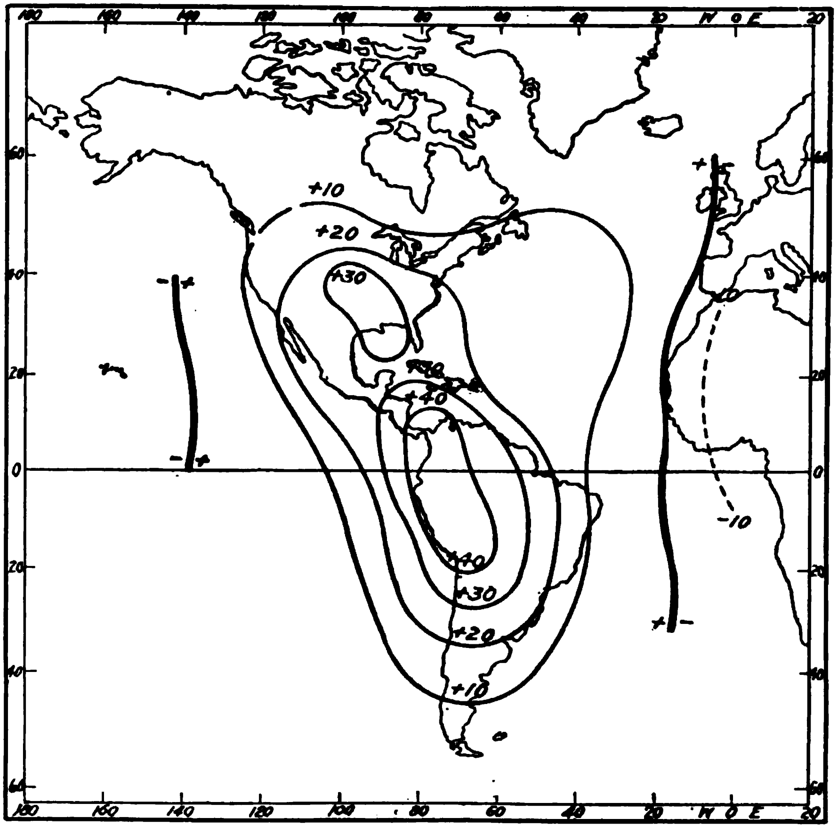


Chart 8.—Diurnal Barometric Wave at 9 a.m., 75th Meridian (Fassig).
(Departures from the mean pressure of the day in thousandths of an inch of mercury.)

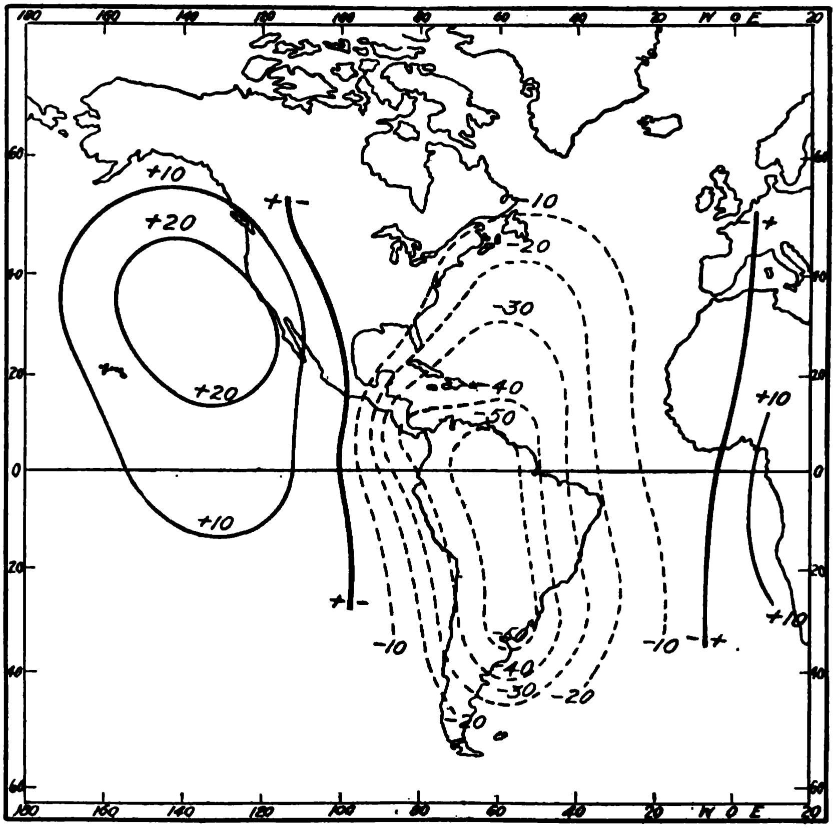


CHART 9.—DIURNAL BAROMETRIC WAVE AT 3 A.M., 75TH MERIDIAN (Fassig).
(Departures from the mean pressure of the day in thousandths of an inch of mercury.)

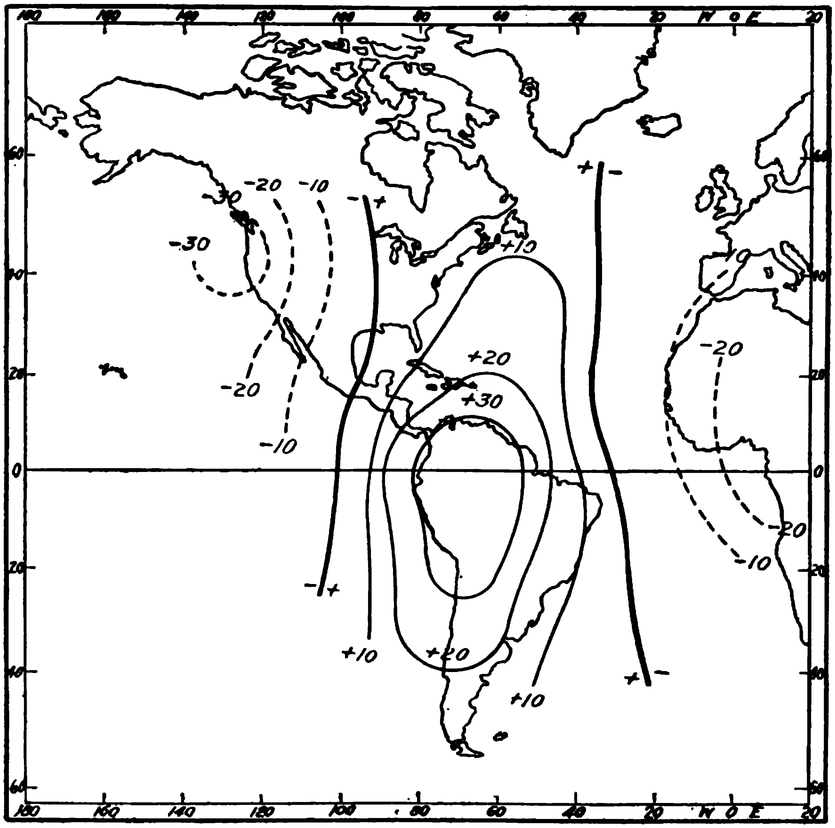


CHART 10.—DIURNAL BAROMETRIC WAVE AT 10 P.M., 75TH MERIDIAN (Fassig).

(Departures from the mean pressure of the day in thousandths of an inch of mercury.)

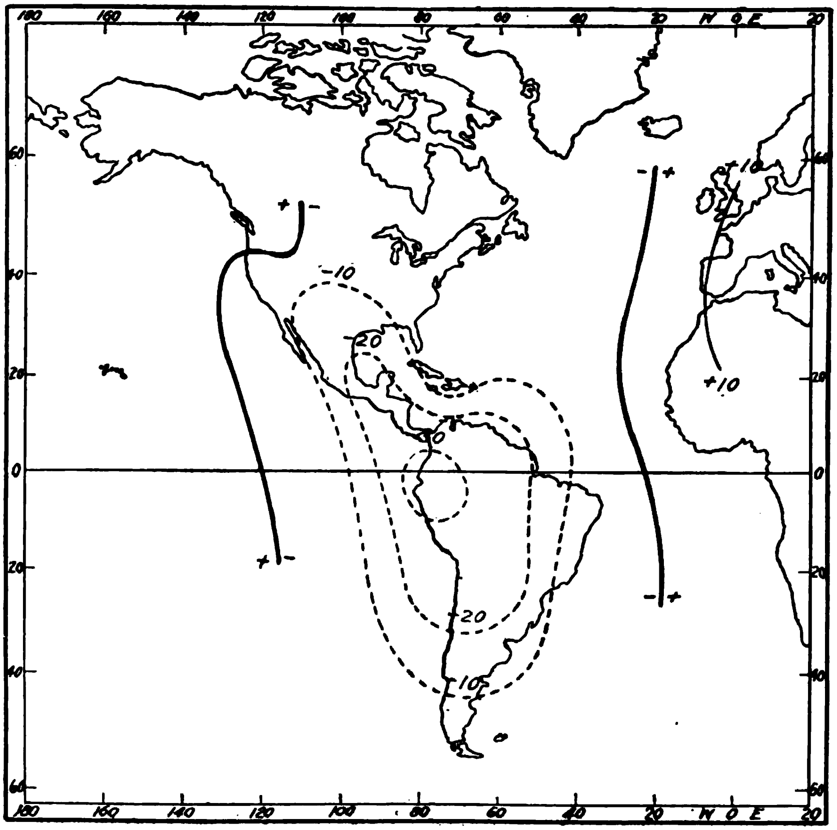


Chart 11.—Diurnal Barometric Wave at 4 a.m., 75th Meridian (Fassig).

(Departures from the mean pressure of the day in thousandths of an inch of mercury.)

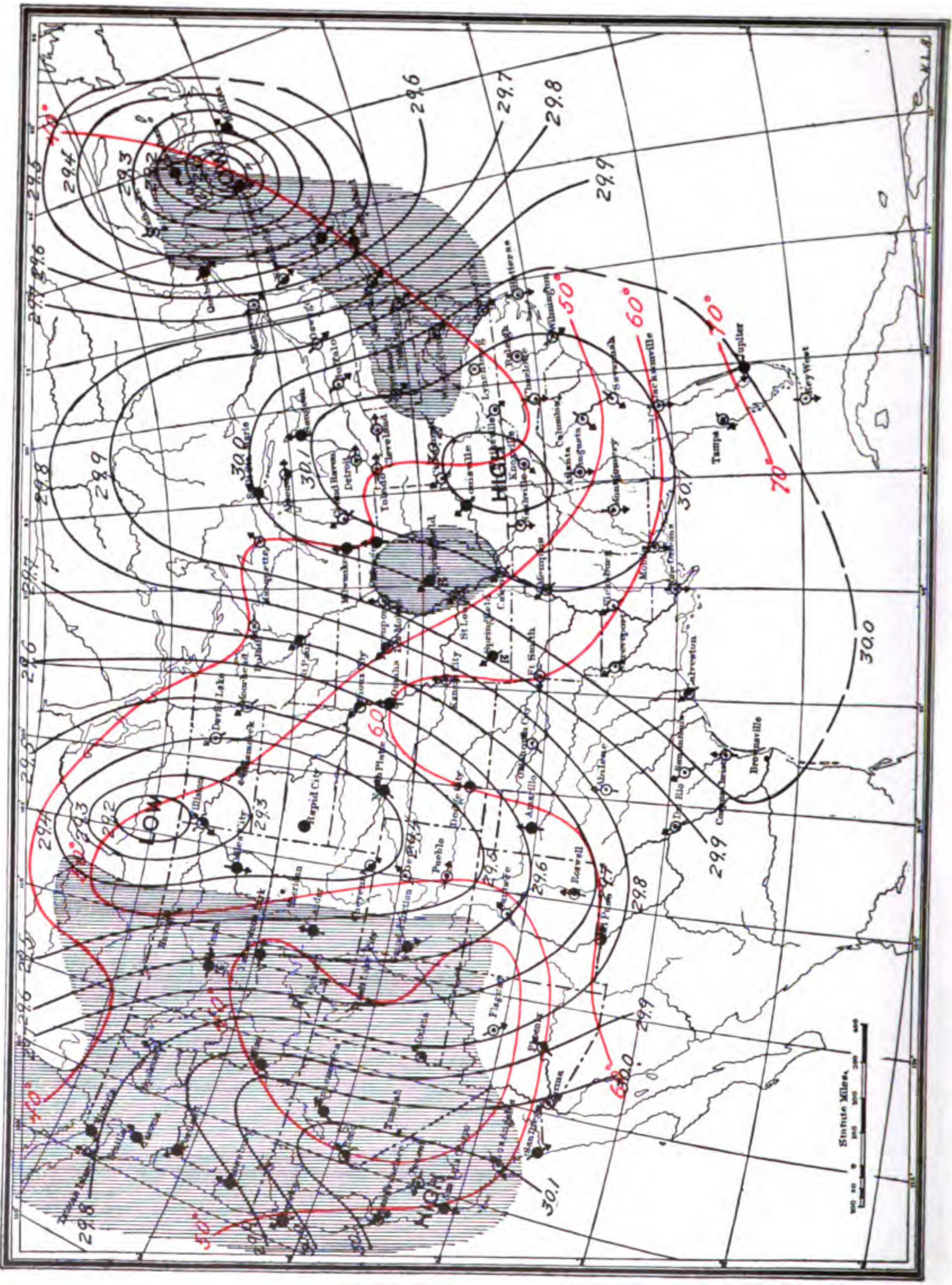


CHART 12.—WEATHER MAP, APRIL 24, 1906.

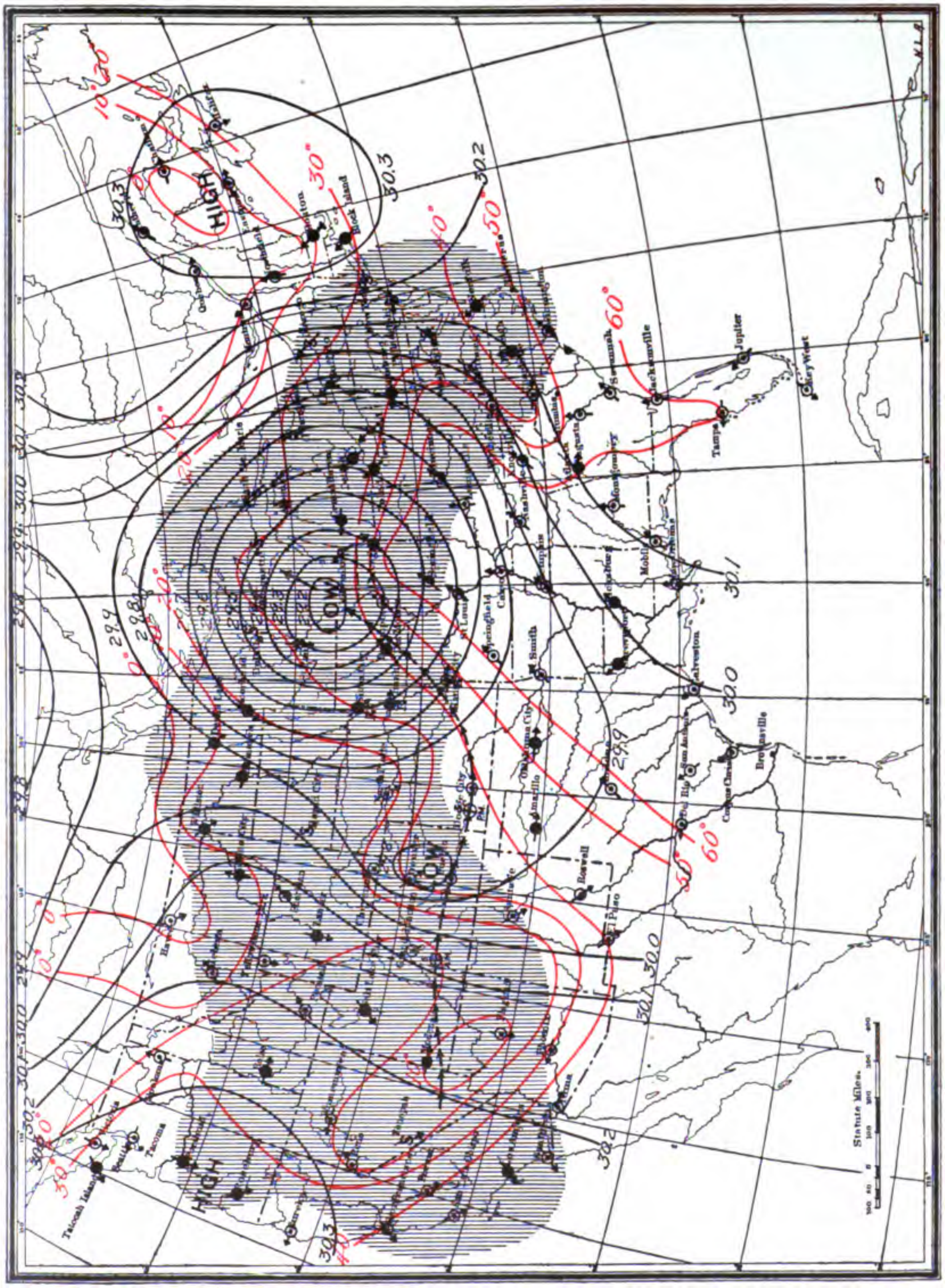


CHART 13.—MORNING WEATHER MAP, MARCH 6, 1908.

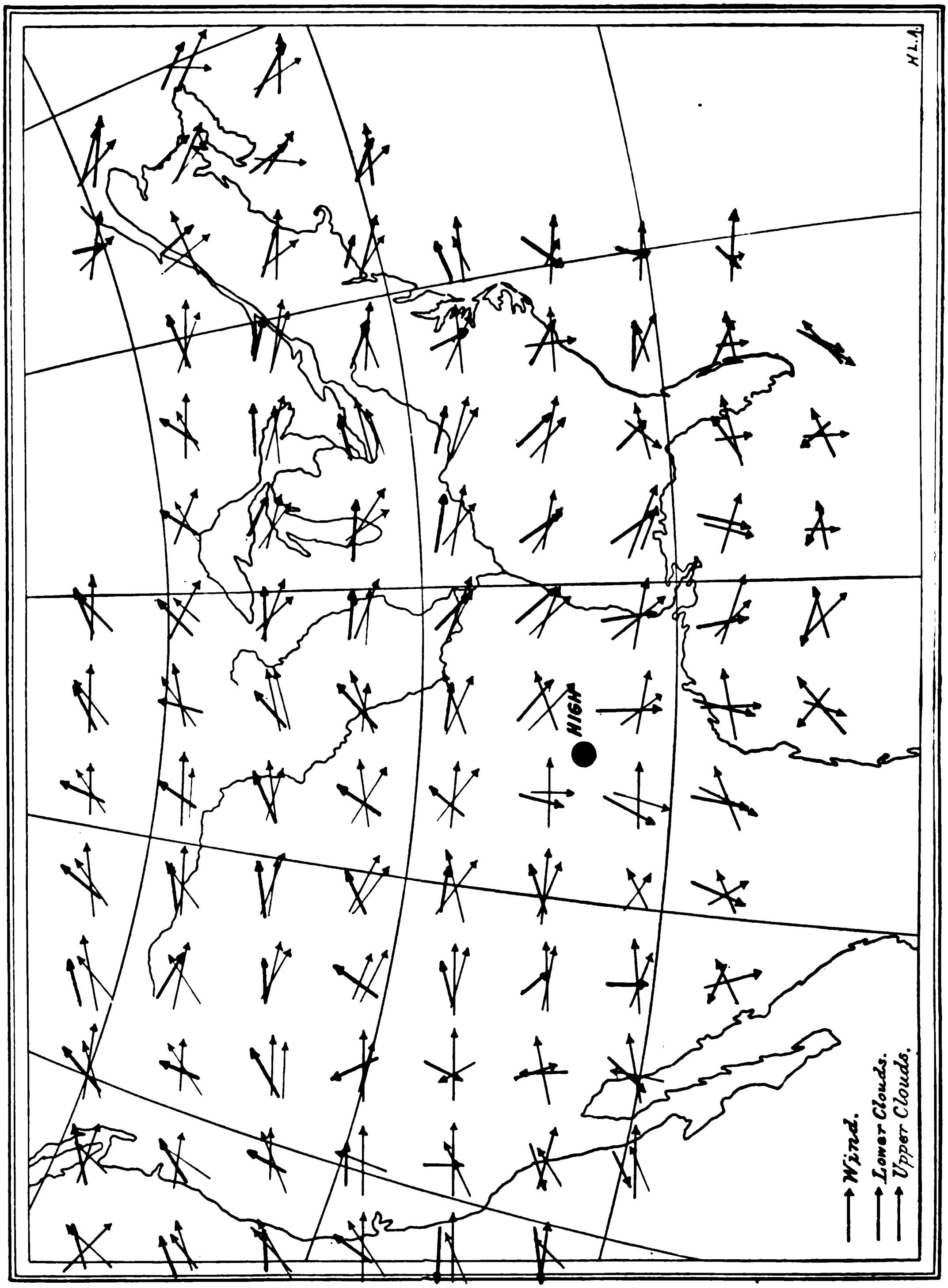


CHART 14. WIND VECTORS FOR WEST GULF HIGH.

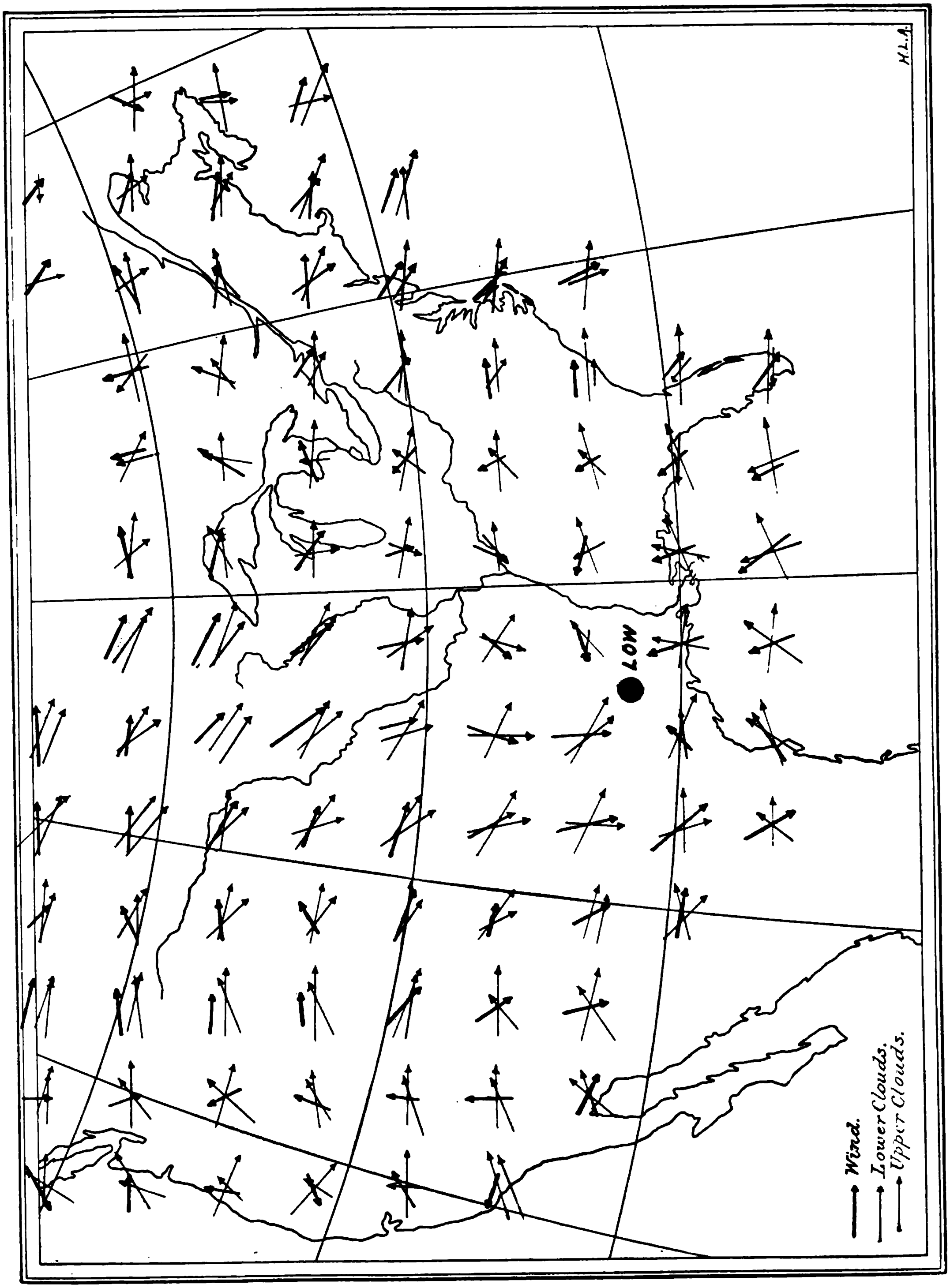


CHART 15.—WIND VECTORS FOR WEST GULF LOW.

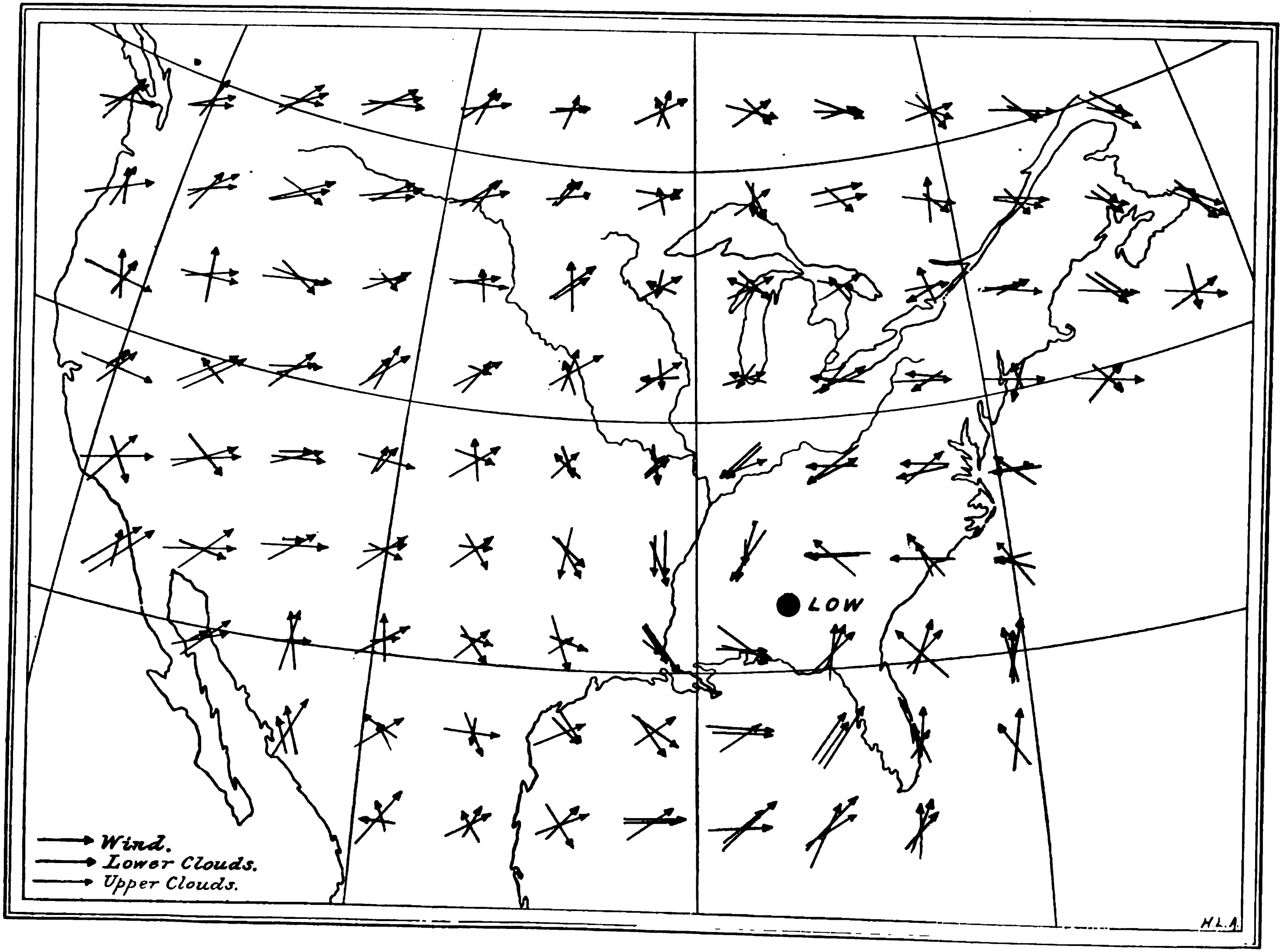


CHART 16. WIND VECTORS IN TROPICAL HURRICANE.

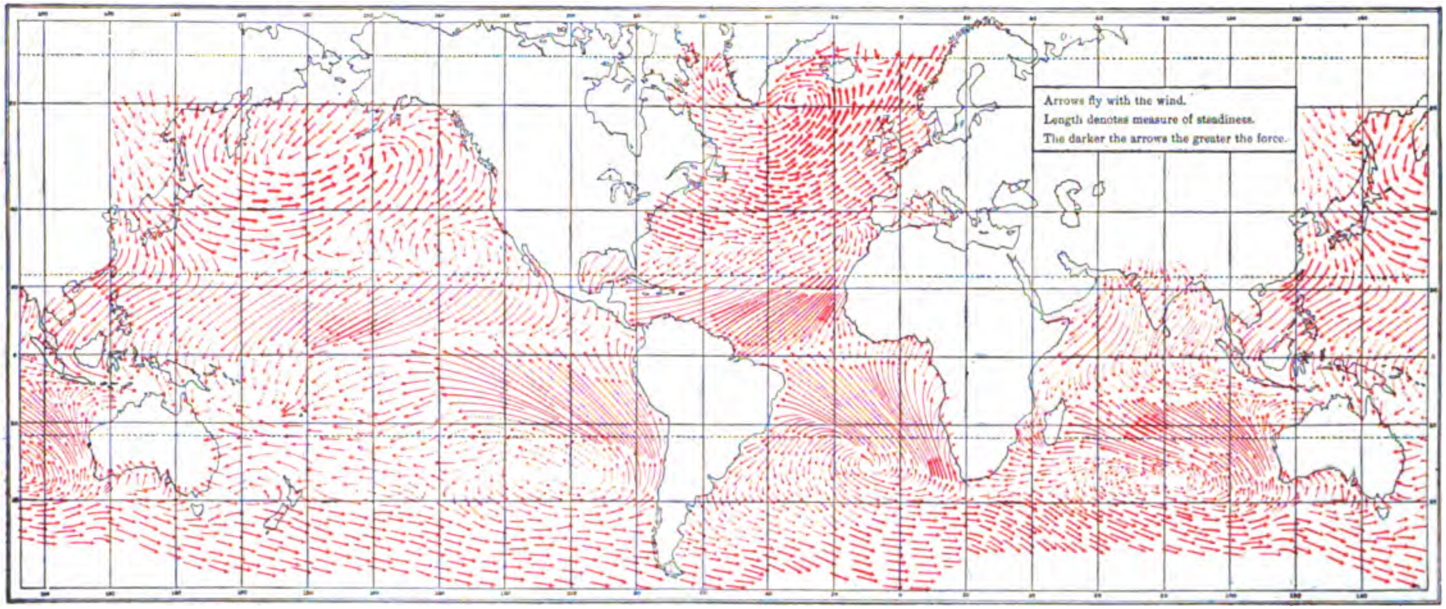

Arrows fly with the wind.
Length denotes measure of steadiness.
The darker the arrows the greater the force.

Chart 17.—Normal Wind Direction and Velocity for January and February (Köppen).

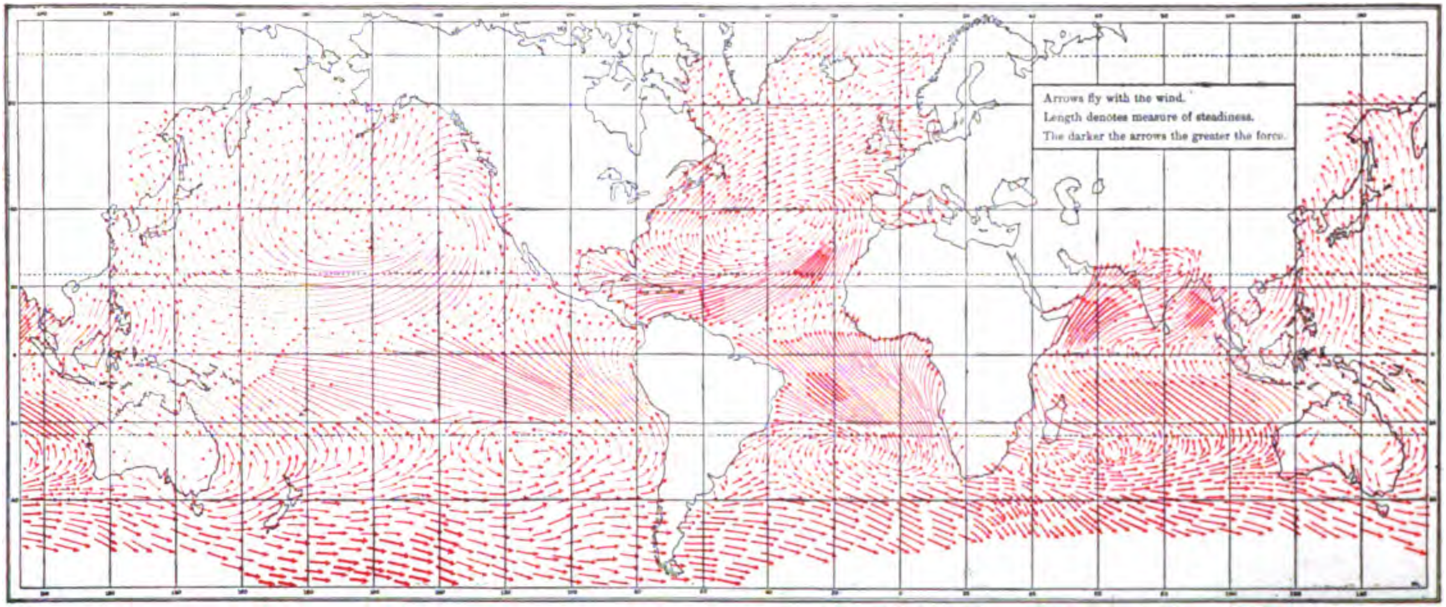
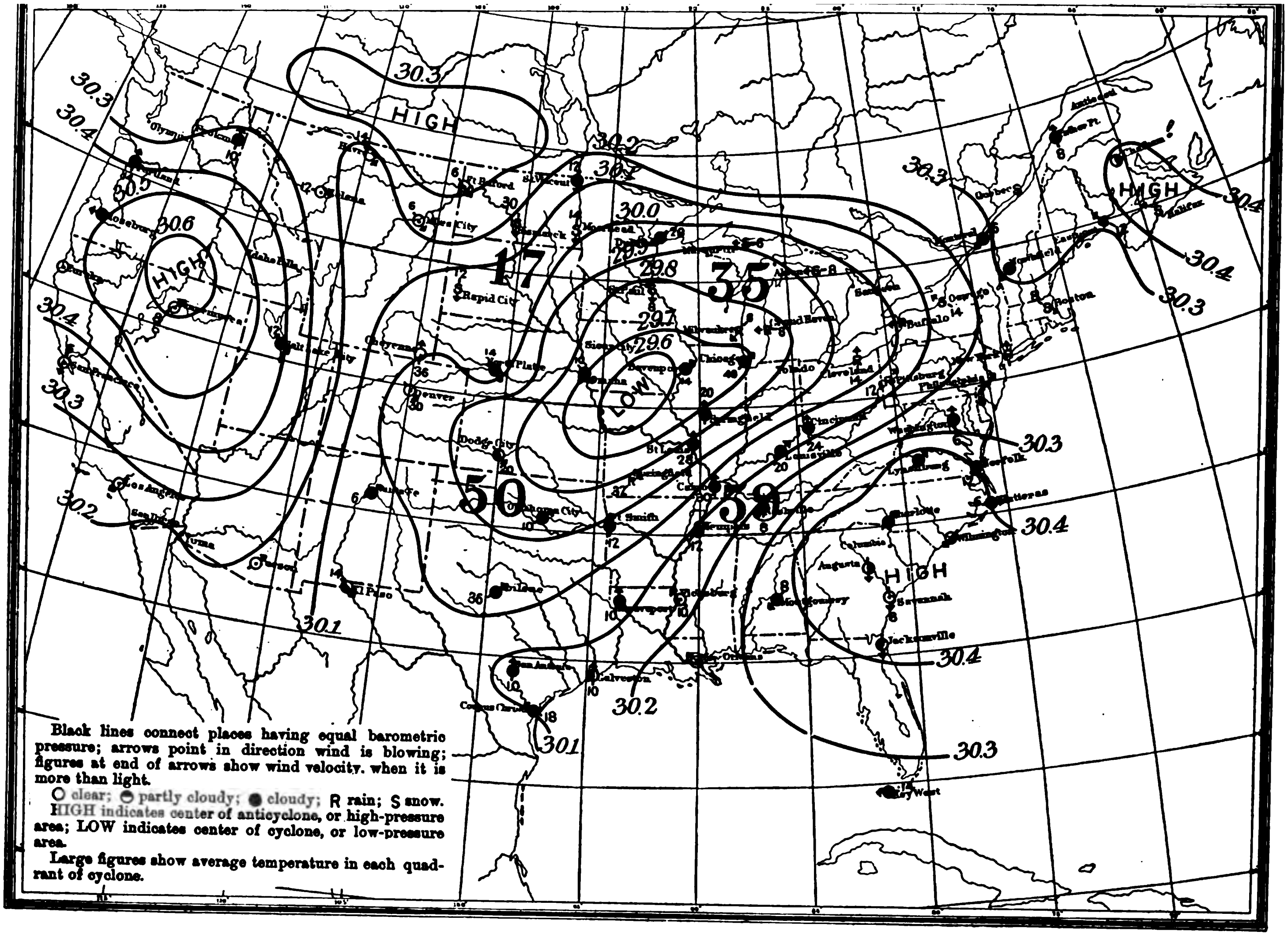

Arrows fly with the wind.
Length denotes measure of steadiness.
The darker the arrows the greater the force.

CHART 18.—NORMAL WIND DIRECTION AND VELOCITY FOR JULY AND AUGUST (Köppen).

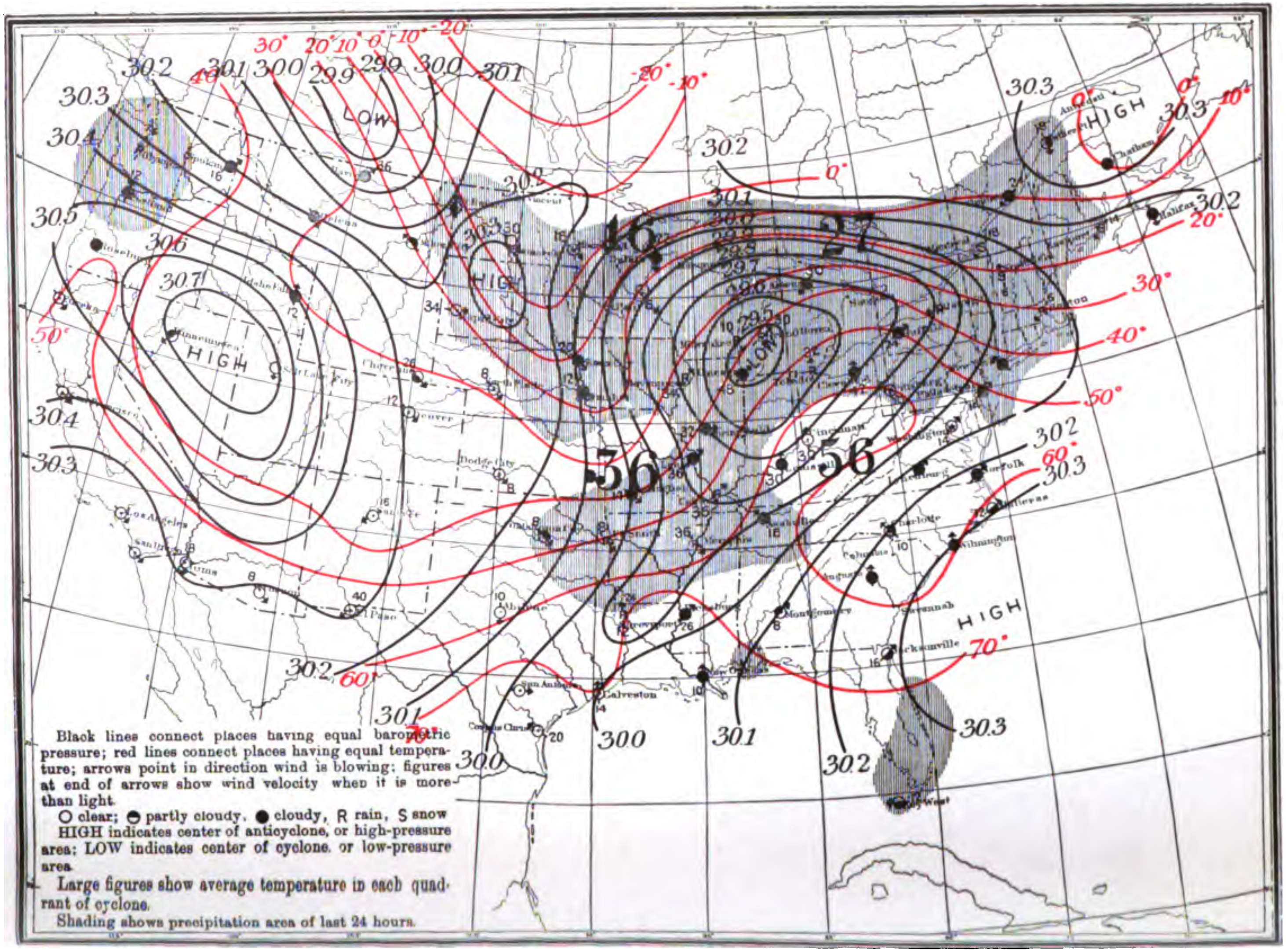


Black lines connect places having equal barometric pressure; arrows point in direction wind is blowing; figures at end of arrows show wind velocity, when it is more than light.

○ clear; ◒ partly cloudy; ● cloudy; R rain; S snow. HIGH indicates center of anticyclone, or high-pressure area; LOW indicates center of cyclone, or low-pressure area.

Large figures show average temperature in each quadrant of cyclone.

CHART 19.—WINTER STORM, DECEMBER 15, 1893. 8 A.M.



Black lines connect places having equal barometric pressure; red lines connect places having equal temperature; arrows point in direction wind is blowing; figures at end of arrows show wind velocity when it is more than light.

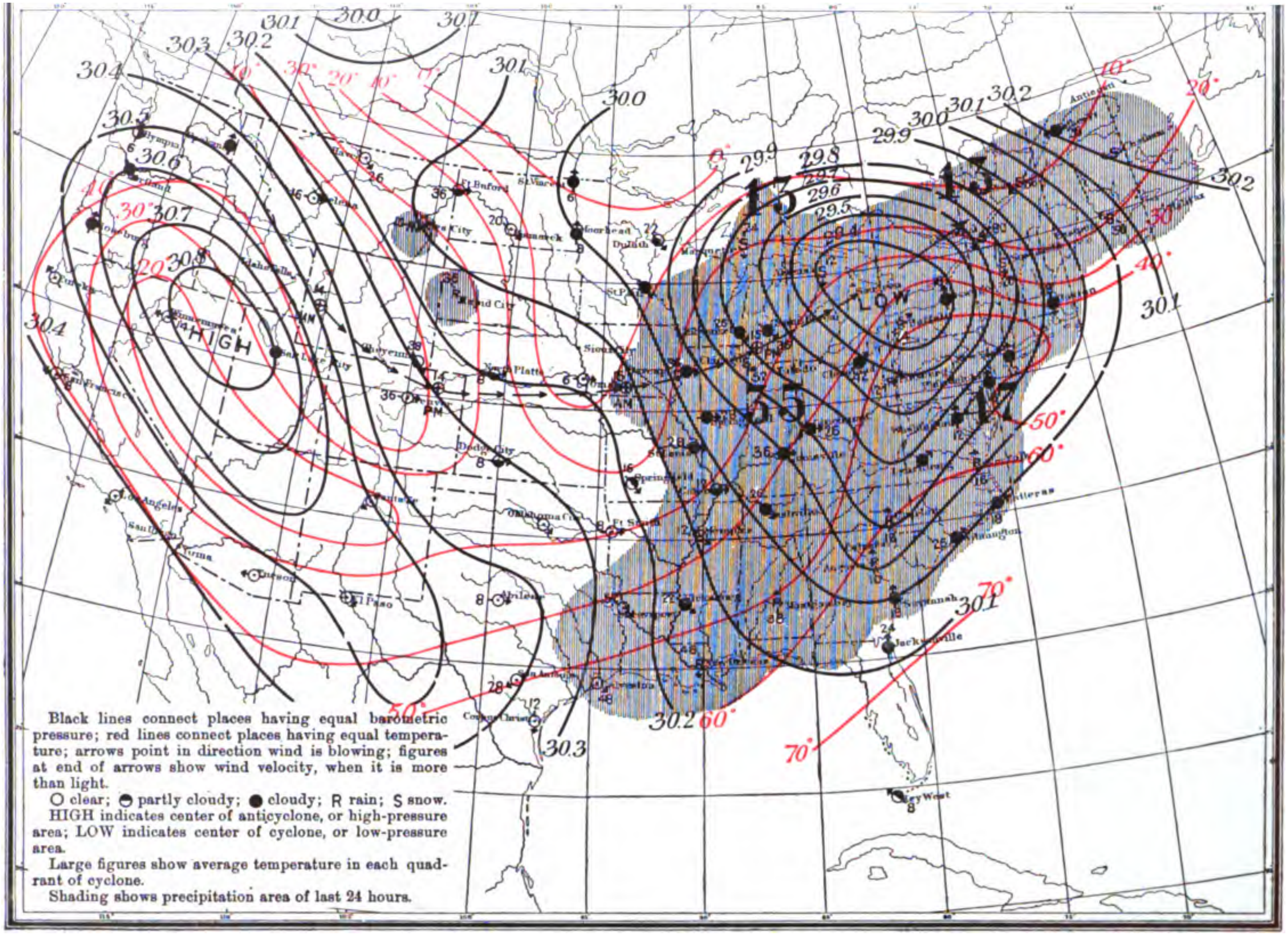
○ clear; ◓ partly cloudy, ● cloudy, R rain, S snow

HIGH indicates center of anticyclone, or high-pressure area; LOW indicates center of cyclone, or low-pressure area.

Large figures show average temperature in each quadrant of cyclone.

Shading shows precipitation area of last 24 hours.

Chart 20.—Weather Bureau, December 15,



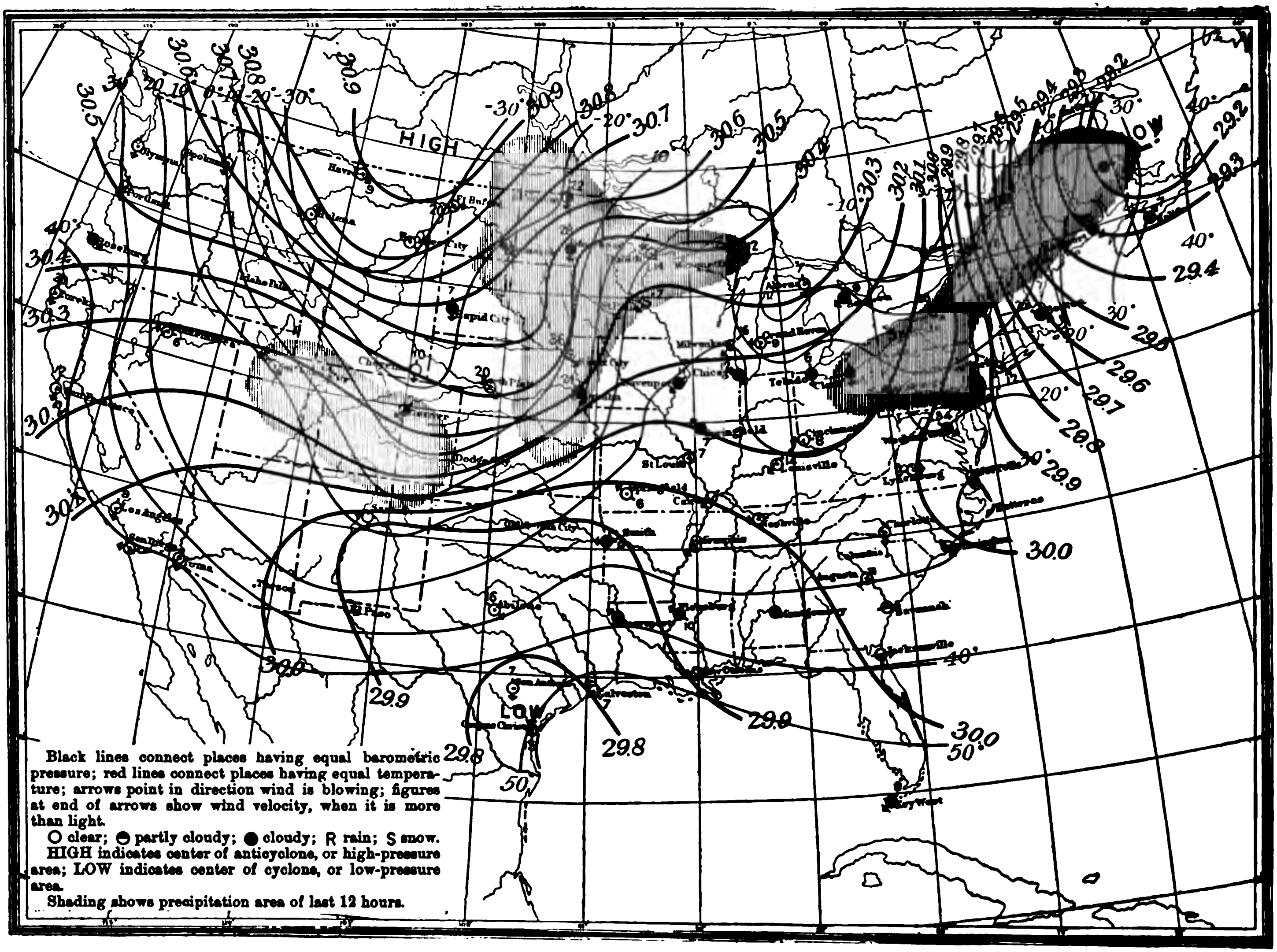
Black lines connect places having equal barometric pressure; red lines connect places having equal temperature; arrows point in direction wind is blowing; figures at end of arrows show wind velocity, when it is more than light.

○ clear; ◓ partly cloudy; ● cloudy; R rain; S snow. HIGH indicates center of anticyclone, or high-pressure area; LOW indicates center of cyclone, or low-pressure area.

Large figures show average temperature in each quadrant of cyclone.

Shading shows precipitation area of last 24 hours.

CHART 21.—WINTER STORM, DECEMBER 16, 1893, 8 A.M.



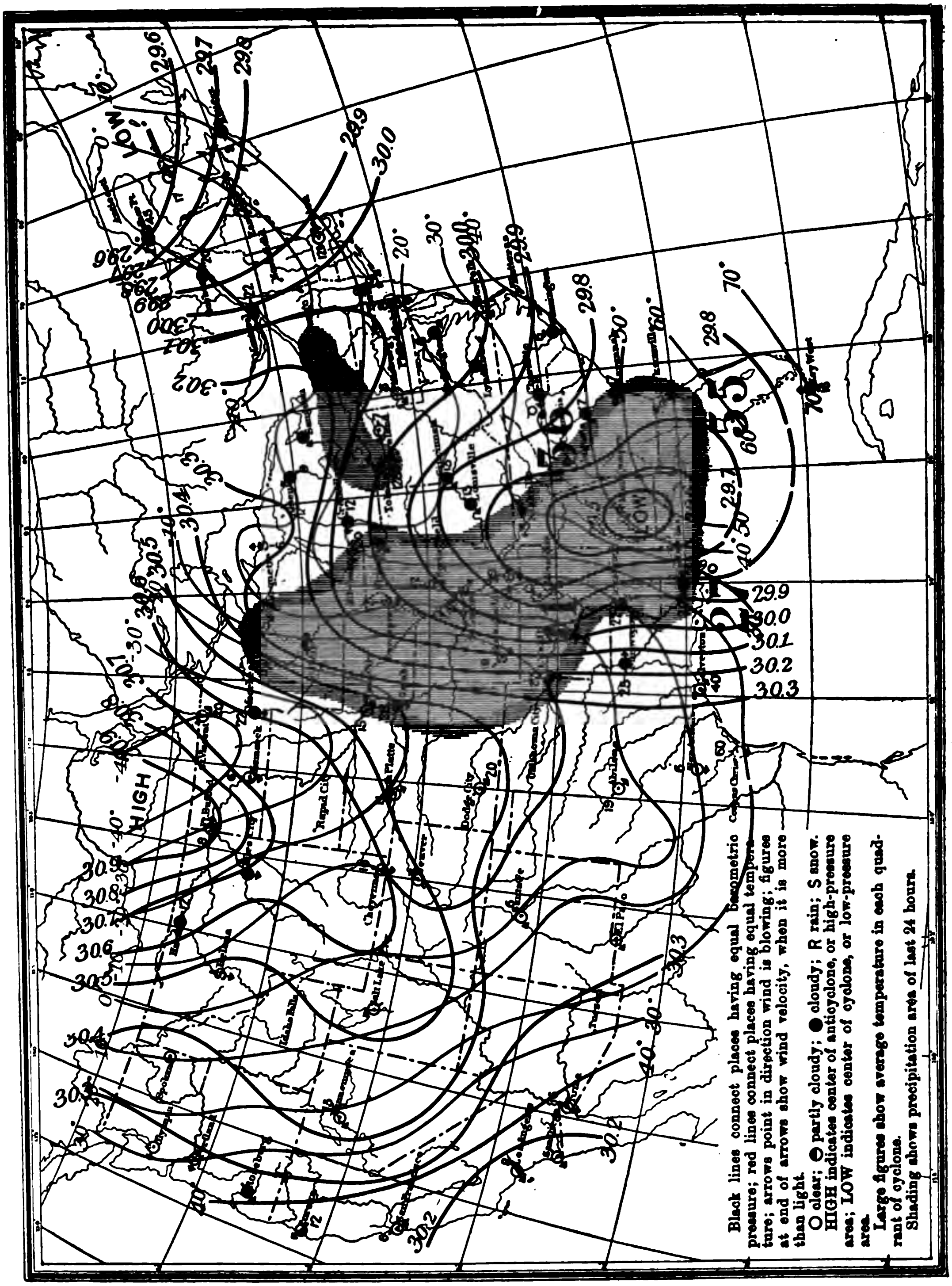
Black lines connect places having equal barometric pressure; red lines connect places having equal temperature; arrows point in direction wind is blowing; figures at end of arrows show wind velocity, when it is more than light.

○ clear; ◒ partly cloudy; ● cloudy; R rain; S snow.

HIGH indicates center of anticyclone, or high-pressure area; LOW indicates center of cyclone, or low-pressure area.

Shading shows precipitation area of last 12 hours.

Chart 22.—Cold Wave, January 7, 1880, 7 a.m.



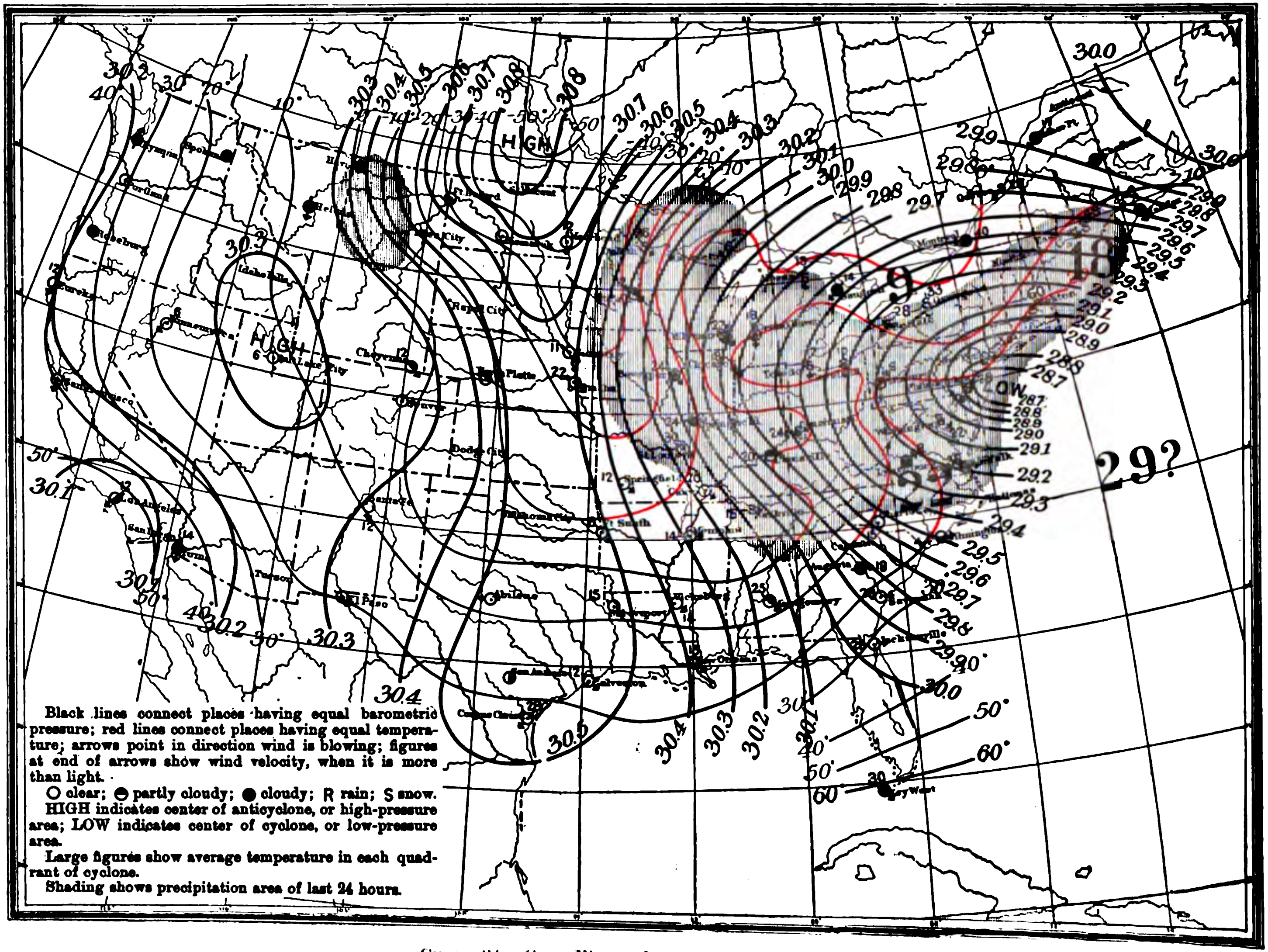
Black lines connect places having equal barometric pressure; red lines connect places having equal temperature; arrows point in direction wind is blowing; figures at end of arrows show wind velocity, when it is more than light.

○ clear; ◐ partly cloudy; ● cloudy; R rain; S snow. HIGH indicates center of anticyclone, or high-pressure area; LOW indicates center of cyclone, or low-pressure area.

Large figures show average temperature in each quadrant of cyclone.

Shading shows precipitation area of last 24 hours.

CHART 23.—COLD WAVE, JANUARY 8, 1886, 7 A.M.



Black lines connect places having equal barometric pressure; red lines connect places having equal temperature; arrows point in direction wind is blowing; figures at end of arrows show wind velocity, when it is more than light.

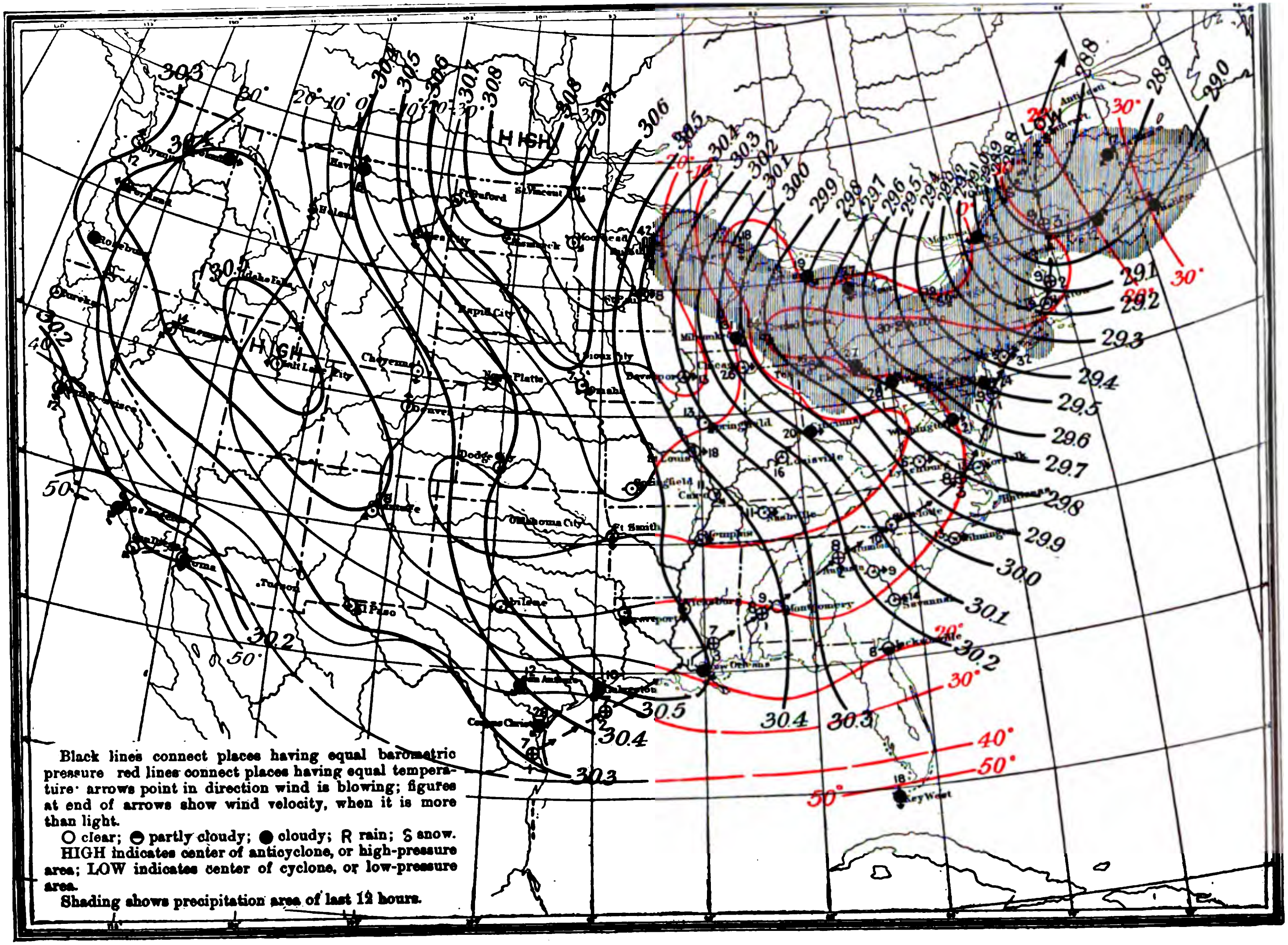
○ clear; ◐ partly cloudy; ● cloudy; R rain; S snow.

HIGH indicates center of anticyclone, or high-pressure area; LOW indicates center of cyclone, or low-pressure area.

Large figures show average temperature in each quadrant of cyclone.

Shading shows precipitation area of last 24 hours.

CHART 24.—COLD WAVE, JANUARY 9, 1886, 7 A.M.



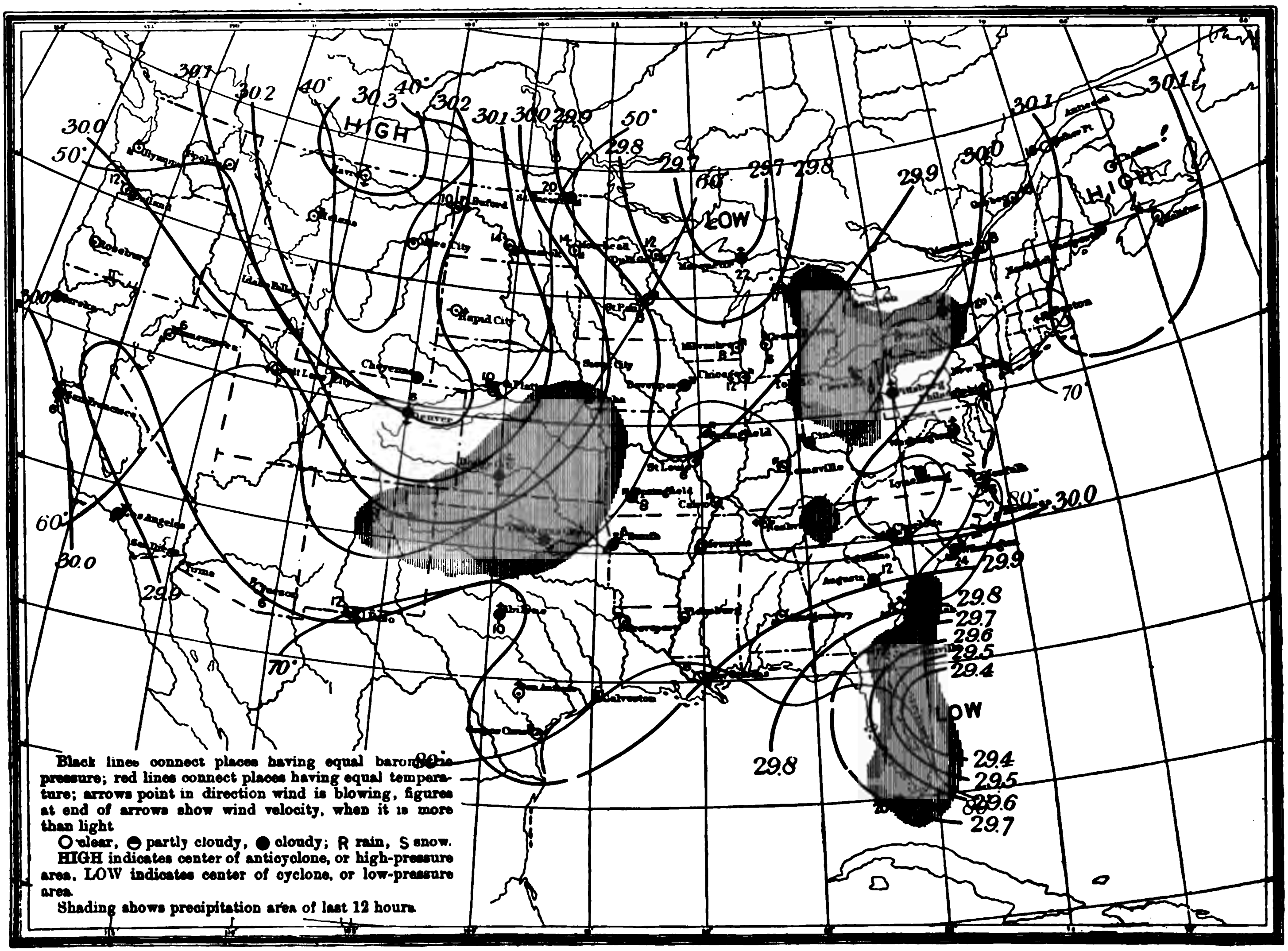
Black lines connect places having equal barometric pressure red lines connect places having equal temperature· arrows point in direction wind is blowing; figures at end of arrows show wind velocity, when it is more than light.

○ clear; ◒ partly cloudy; ● cloudy; R rain; S snow.

HIGH indicates center of anticyclone, or high-pressure area; LOW indicates center of cyclone, or low-pressure area.

Shading shows precipitation area of last 12 hours.

CHART 25.—COLD WAVE, JANUARY 10, 1886, 7 A.M.

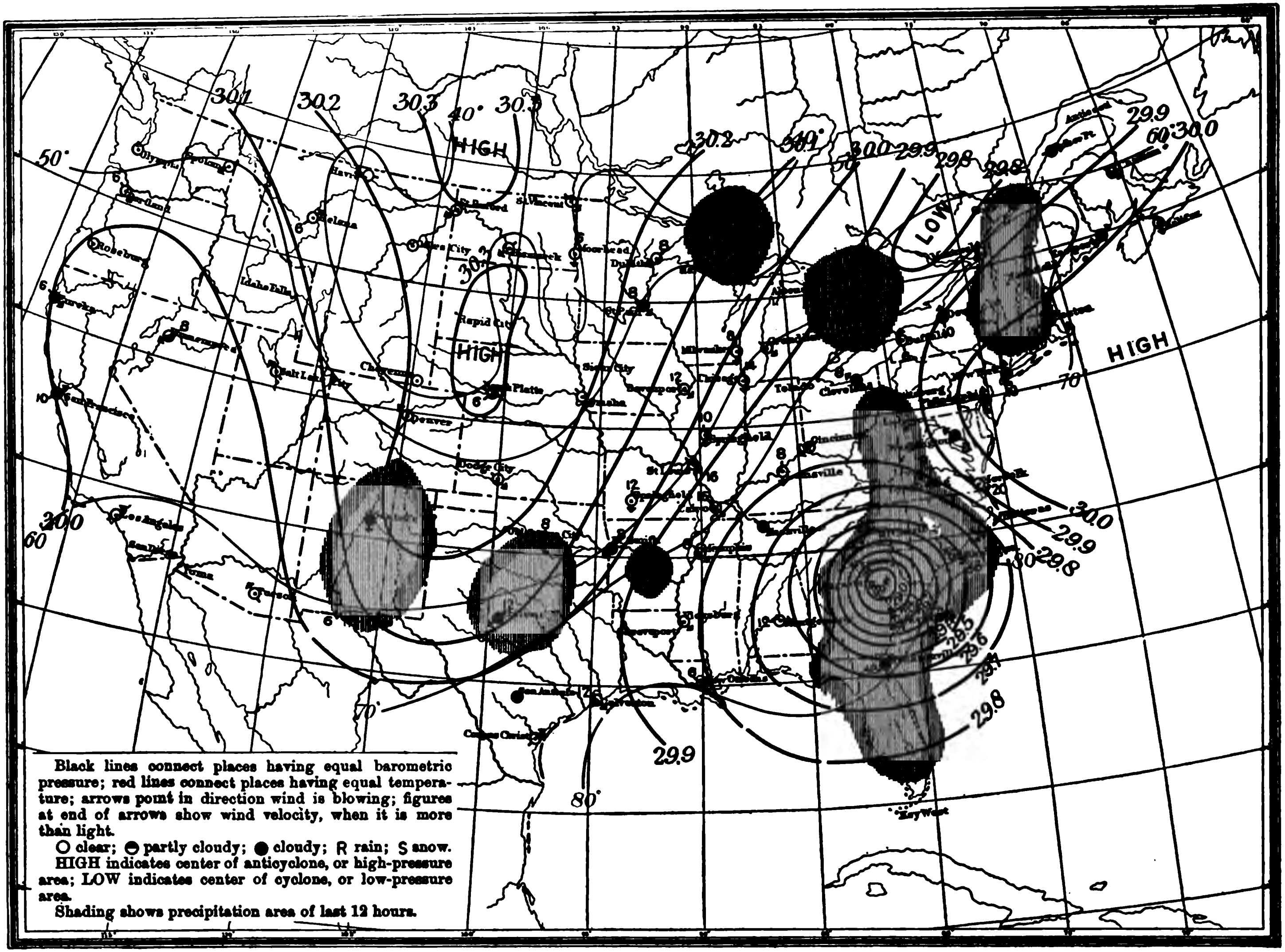


Black lines connect places having equal barometric pressure; red lines connect places having equal temperature; arrows point in direction wind is blowing, figures at end of arrows show wind velocity, when it is more than light

○ clear, ◐ partly cloudy, ● cloudy; R rain, S snow. HIGH indicates center of anticyclone, or high-pressure area. LOW indicates center of cyclone, or low-pressure area.

Shading shows precipitation area of last 12 hours.

Chart 26.—West Indian Hurricane, August 27, 1893, 8 a.m.



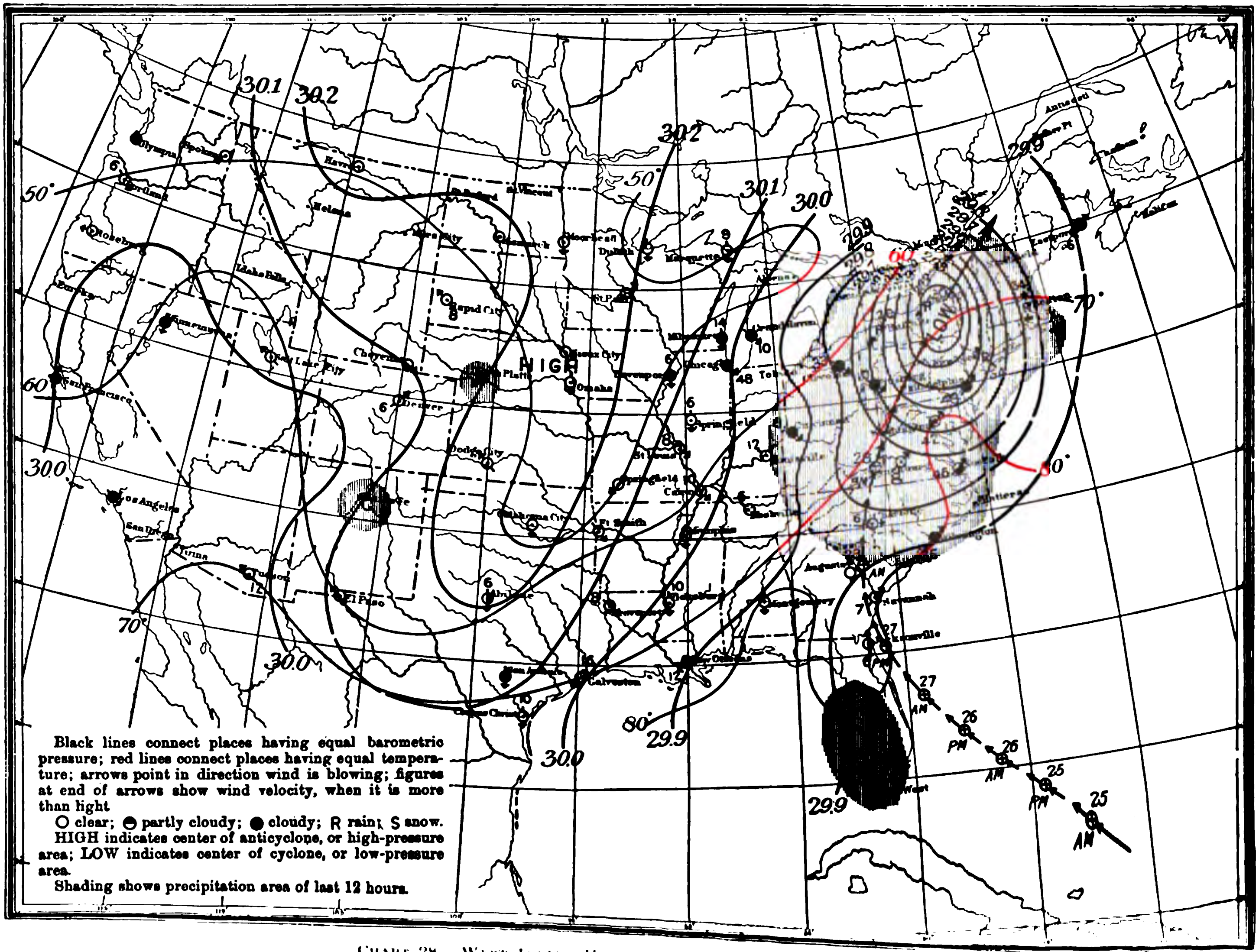
Black lines connect places having equal barometric pressure; red lines connect places having equal temperature; arrows point in direction wind is blowing; figures at end of arrows show wind velocity, when it is more than light.

○ clear; ◒ partly cloudy; ● cloudy; R rain; S snow.

HIGH indicates center of anticyclone, or high-pressure area; LOW indicates center of cyclone, or low-pressure area.

Shading shows precipitation area of last 12 hours.

Chart 27.—West Indian Hurricane, August 28, 1893, 8 a.m.



Black lines connect places having equal barometric pressure; red lines connect places having equal temperature; arrows point in direction wind is blowing; figures at end of arrows show wind velocity, when it is more than light

○ clear; ◓ partly cloudy; ● cloudy; R rain; S snow.

HIGH indicates center of anticyclone, or high-pressure area; LOW indicates center of cyclone, or low-pressure area.

Shading shows precipitation area of last 12 hours.

CHART 28.—WEST INDIAN HURRICANE.—AUGUST 29, 1893, 8 A.M.

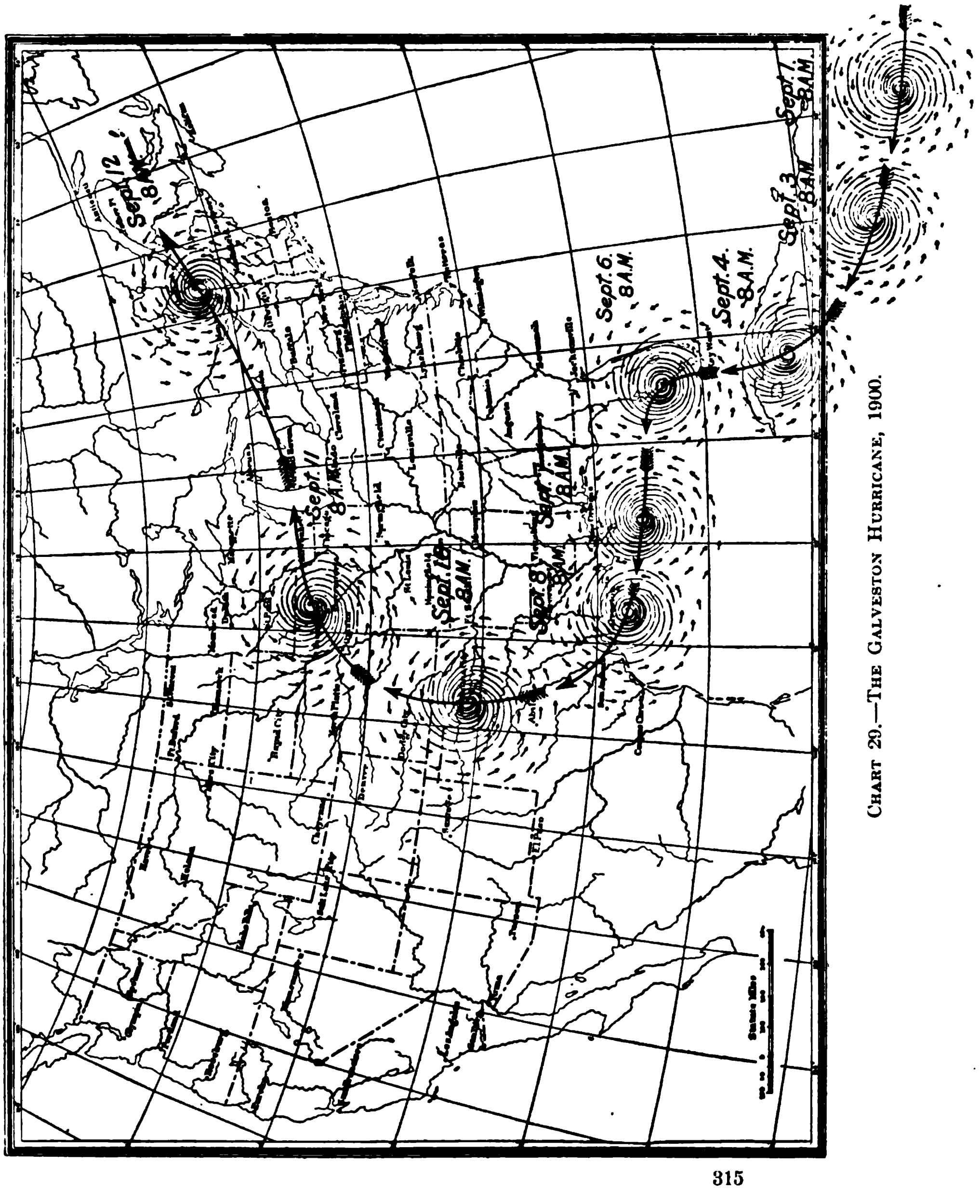


CHART 29.—THE GALVESTON HURRICANE, 1900.

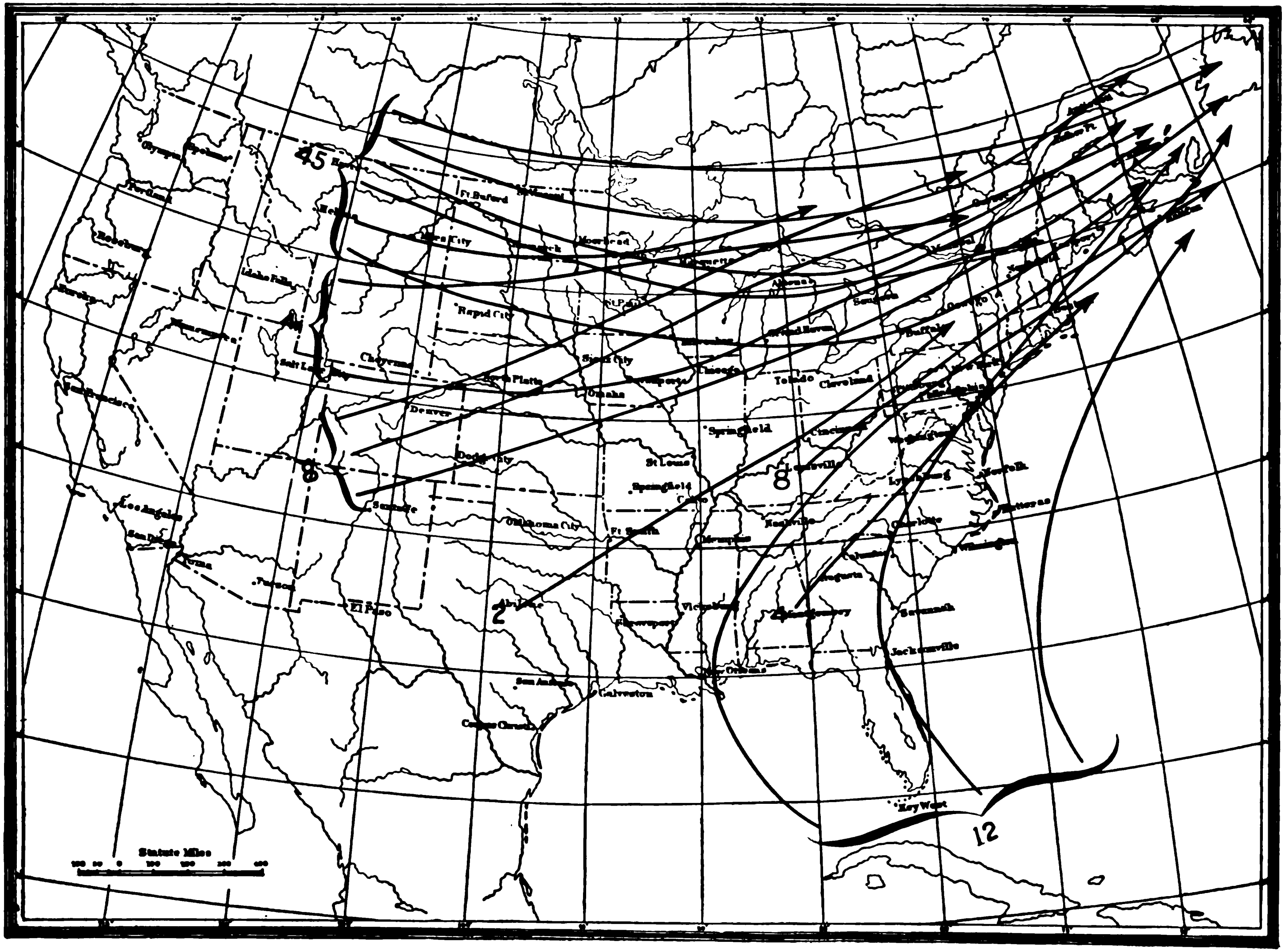


CHART 30.—STORM TRACKS FOR AUGUST FOR 10 YEARS.

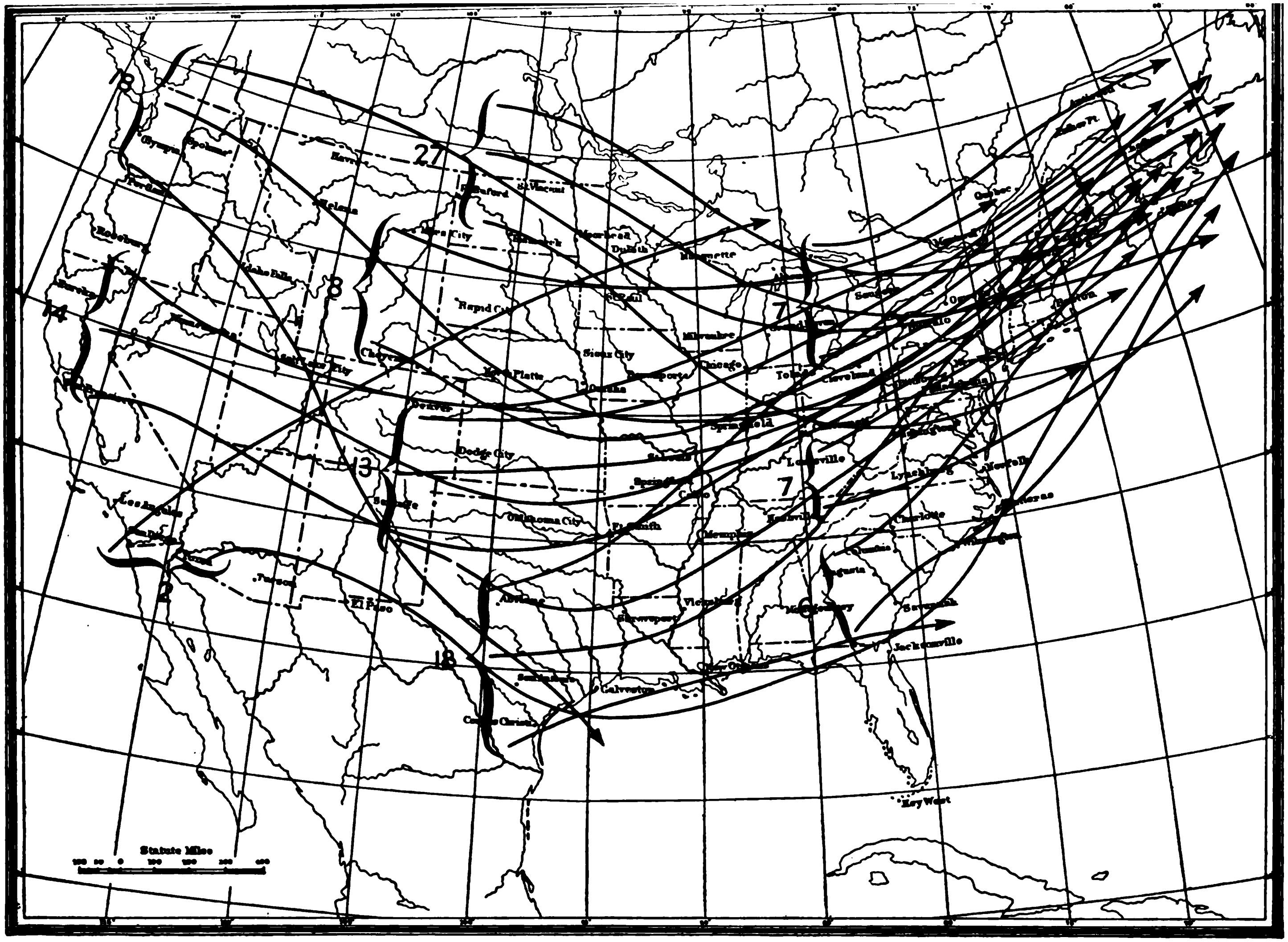


CHART 31.—STORM TRACKS FOR FEBRUARY FOR 10 YEARS.

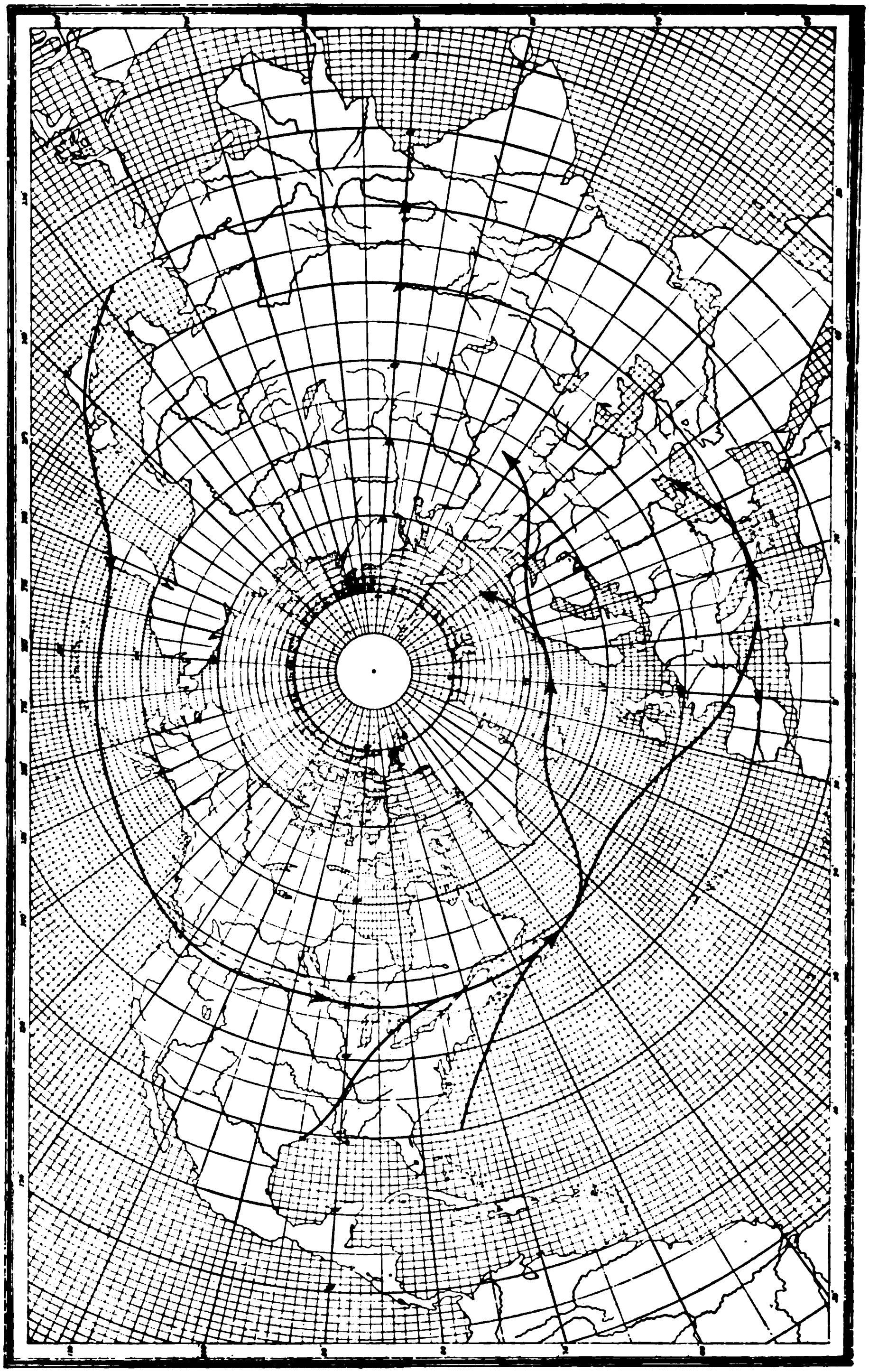


CHART 32.—THE AVERAGE LINES ALONG WHICH THE CENTERS OF STORMS MOVE IN JANUARY IN THE NORTHERN HEMISPHERE.

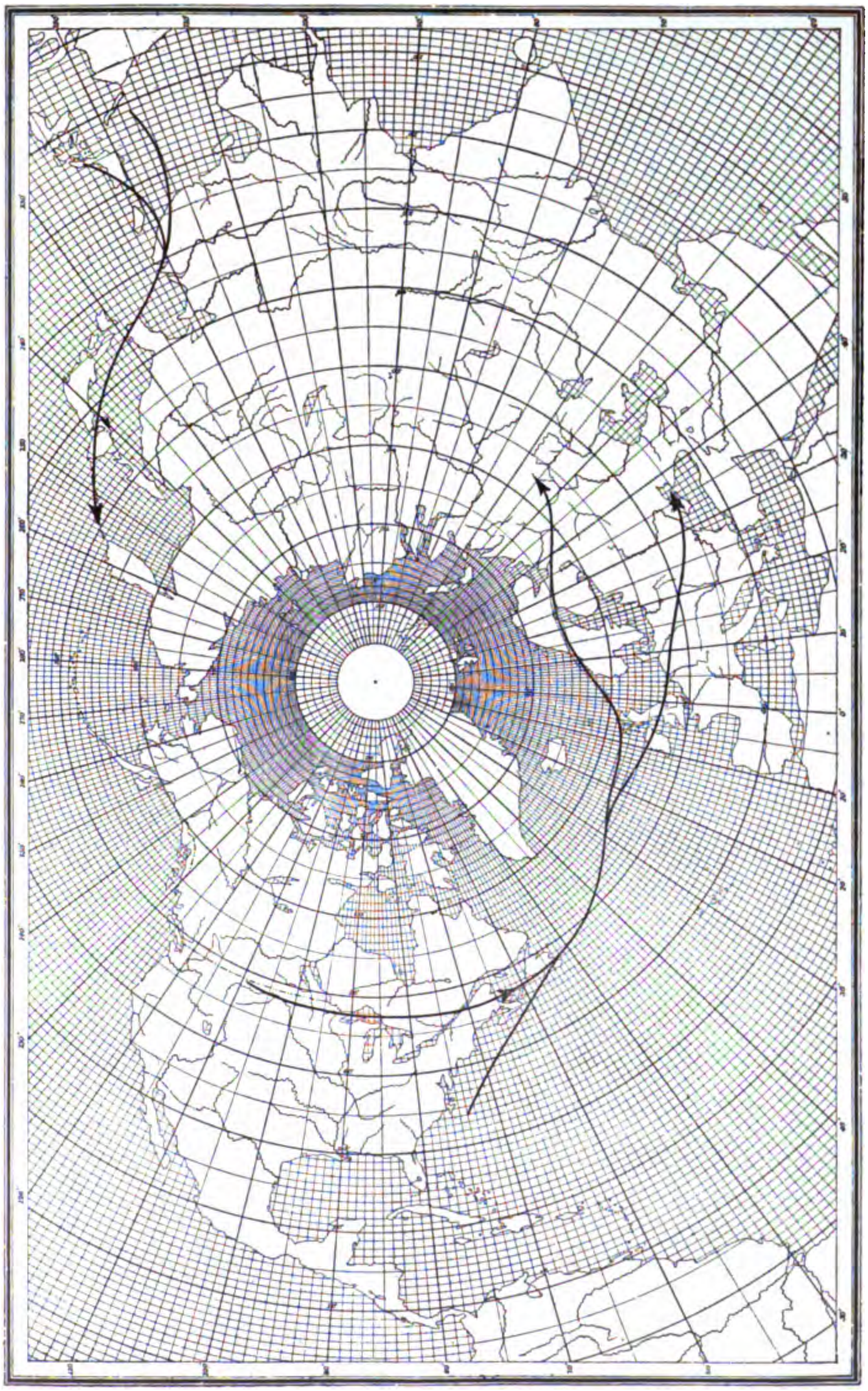
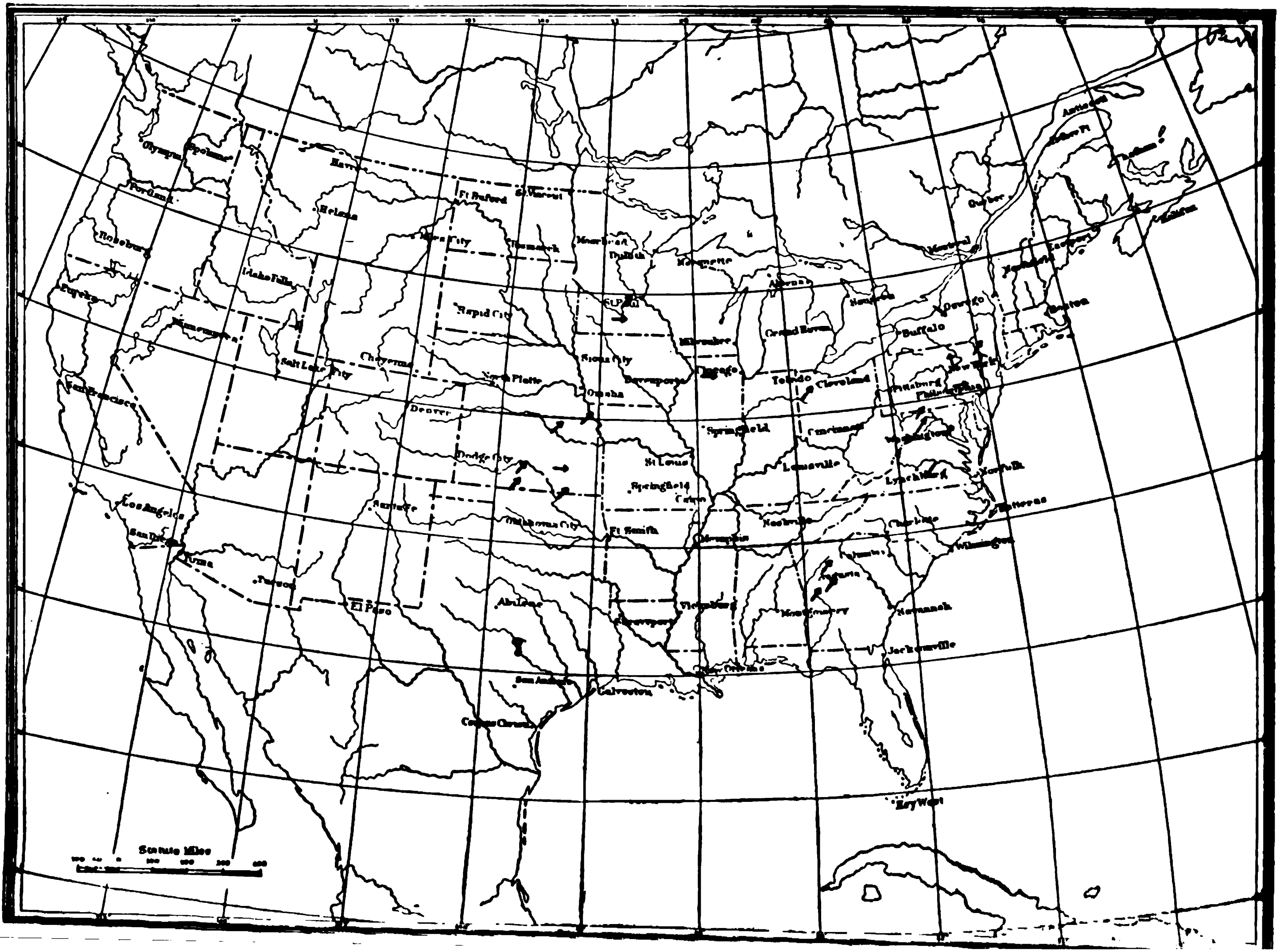


CHART 33.—THE AVERAGE LINES ALONG WHICH THE CENTERS OF STORMS MOVE IN JULY IN THE NORTHERN HEMISPHERE.


Olympia
Spokane
Havre
Portland
Helena
Ft Buford
St Vincent
Roseburg
Miles City
Bismarck
Moorhead
Duluth
Marquette
Idaho Falls
Eureka
Winnemucca
Rapid City
St Paul
Alpena
Cheyenne
Salt Lake City
North Platte
Sioux City
Milwaukee
Grand Haven
Buffalo
Oswego
Boston
Quebec
Montreal
Anticosti
Father Pt
Eastport
Halifax
San Francisco
Denver
Omaha
Davenport
Chicago
Toledo
Cleveland
Pittsburg
Philadelphia
New York
Springfield
Cincinnati
Washington
Dodge City
St Louis
Louisville
Springfield
Cairo
Lynchburg
Norfolk
Hatteras
Los Angeles
Santa Fe
Oklahoma City
Ft Smith
Memphis
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San Diego
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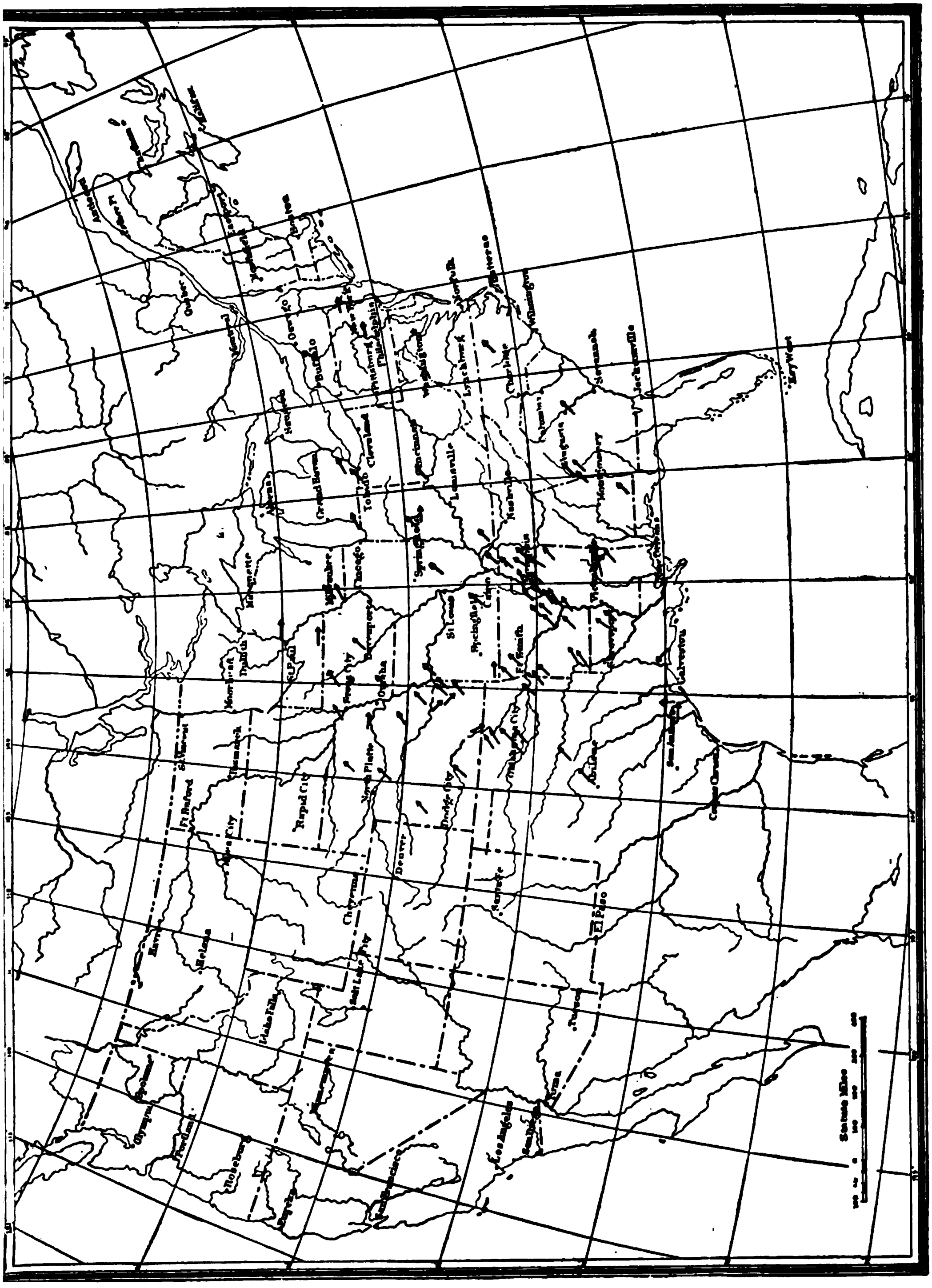

CHART 35.—TORNADOES OF 1893—A YEAR OF GREAT FREQUENCY.

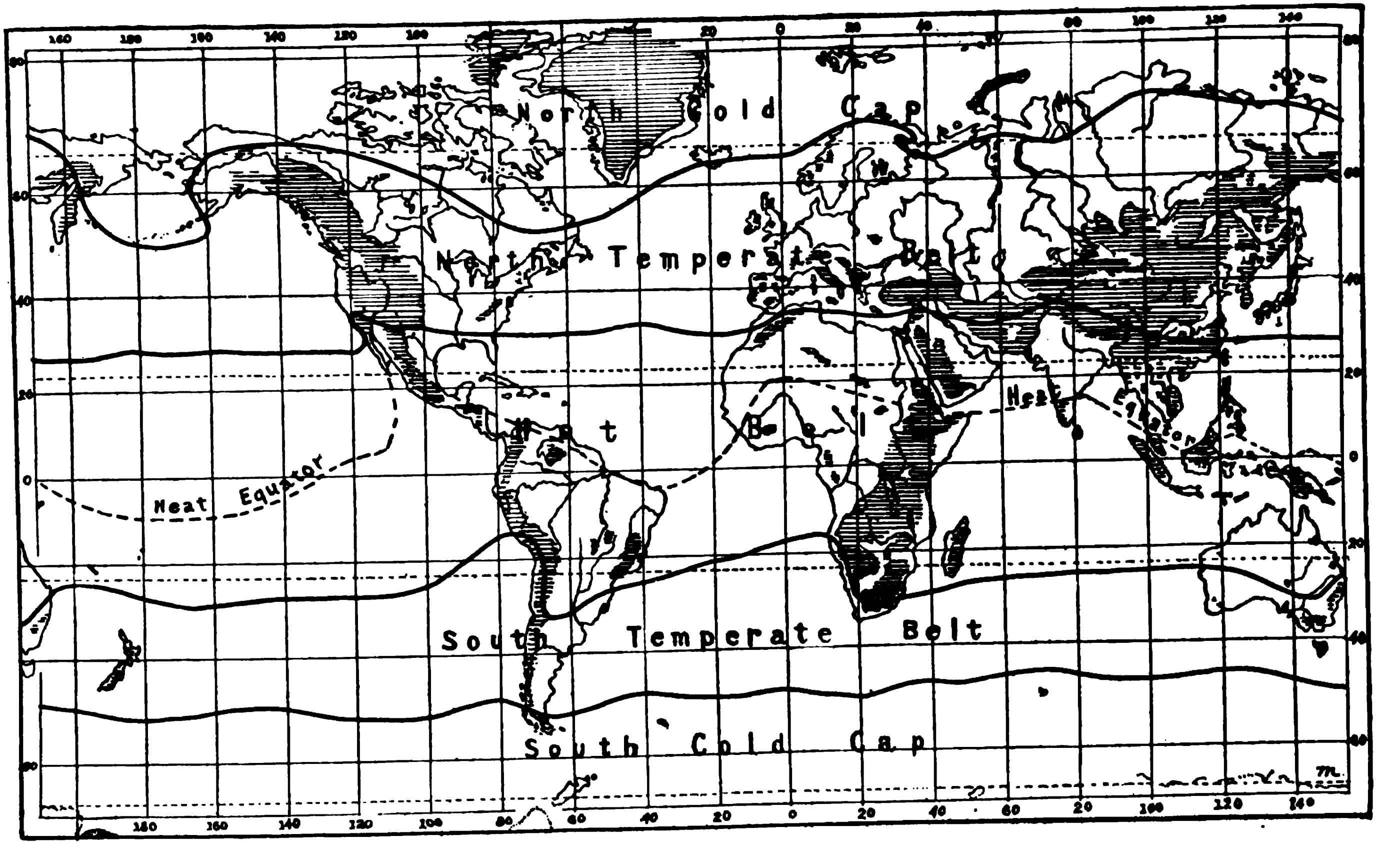

CHART 36.—SUPAN'S TEMPERATURE ZONES (*Bartholomew's Physical Atlas*).

The Plateau area above 3,000 feet is shown by shading.

The Heat Equator, or the line of maximum mean annual temperature, is shown by the dotted line.
The Hot Belt is bounded to north and south by the isotherm representing the mean annual temperature of 20° C. (68° F.).
The Temperature Belts lie between these lines and the isotherm of 10° C. (50° F.) for the warmest month
The Cold Caps cover the regions round the poles to the isotherm of 10° C. (50° F.) for the warmest month.

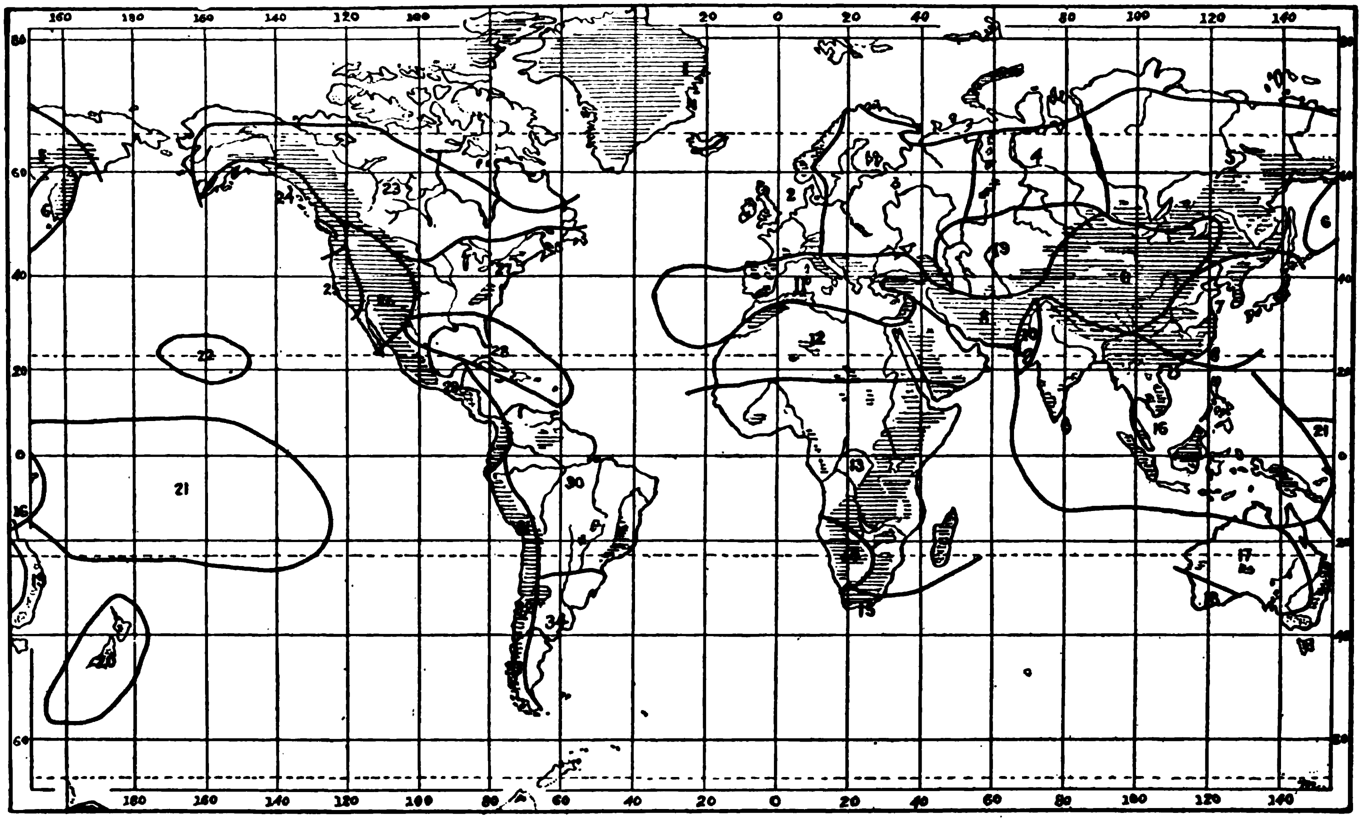

CHART 37.—SUPAN'S CLIMATIC PROVINCES (*Bartholomew's Physical Atlas*).

The Plateau area above 3,000 *feet is shown by shading.*

1. Arctic. 2. West European. 3. East European. 4. West Siberian. 5. East Siberian. 6. Kamchatkan. 7. Sino-Japanese. 8. Asiatic Mountain and Plateau. 9. Aral. 10. Indus. 11. Mediterranean. 12. Saharan. 13. African Tropical. 14. Kalahari. 15. Cape. 16. Indo-Australian Monsoon. 17. Inner Australian. 18. Southwest Australian. 19. East Australian. 20. New Zealand. 21. Polynesian Tropical. 22. Hawaiian. 23. Hudson (North Canadian). 24. Northwest American Coastal. 25. Californian. 26. North American Mountain and Plateau. 27. Atlantic (East North American). 28. West Indian. 29. Tropical Cordilleran. 30. South American Tropical. 31. Peruvian. 32. North Chilian. 33. South Chilian. 34. Pampa.

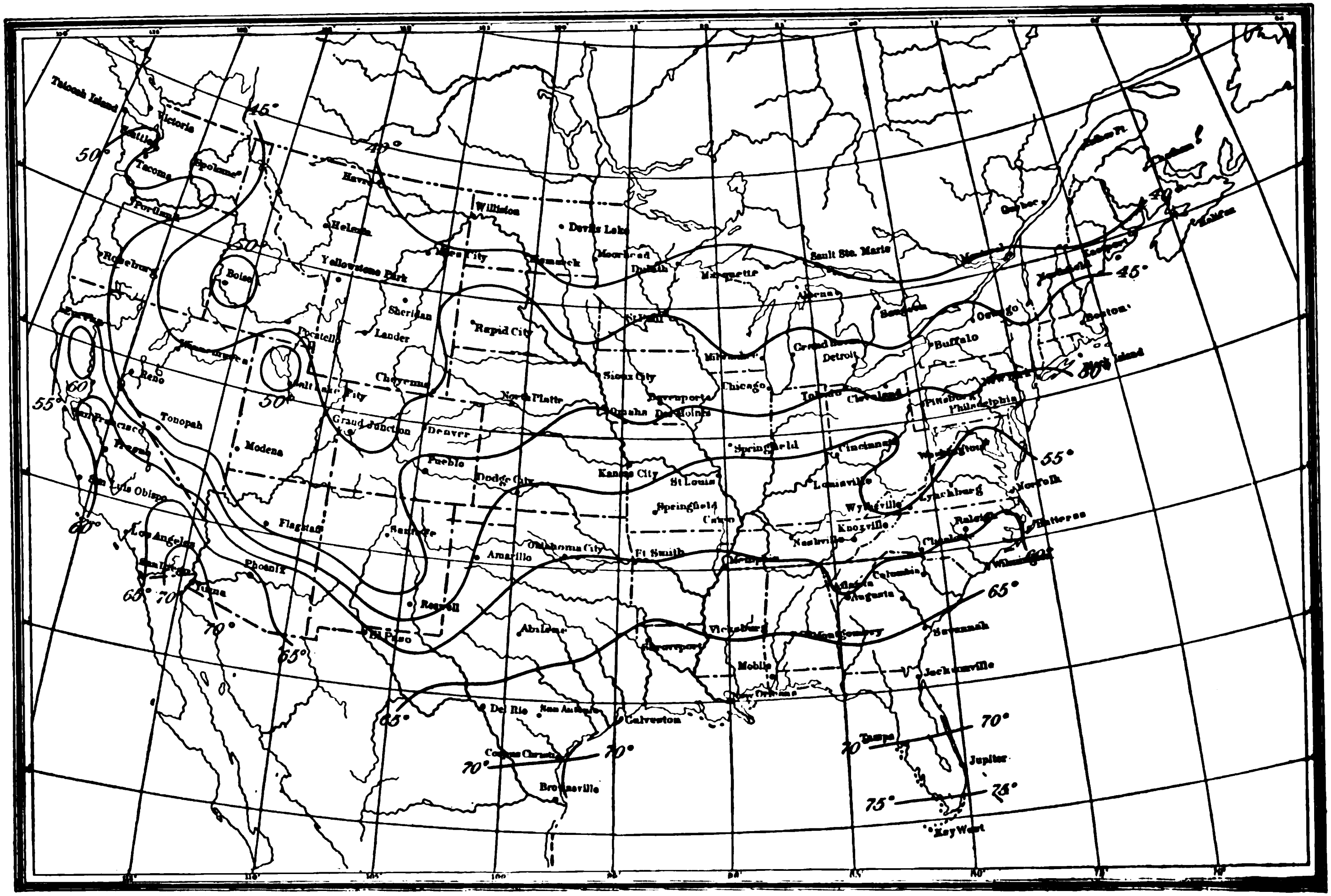

CHART 38.—NORMAL SURFACE TEMPERATURES FOR THE YEAR (Henry).

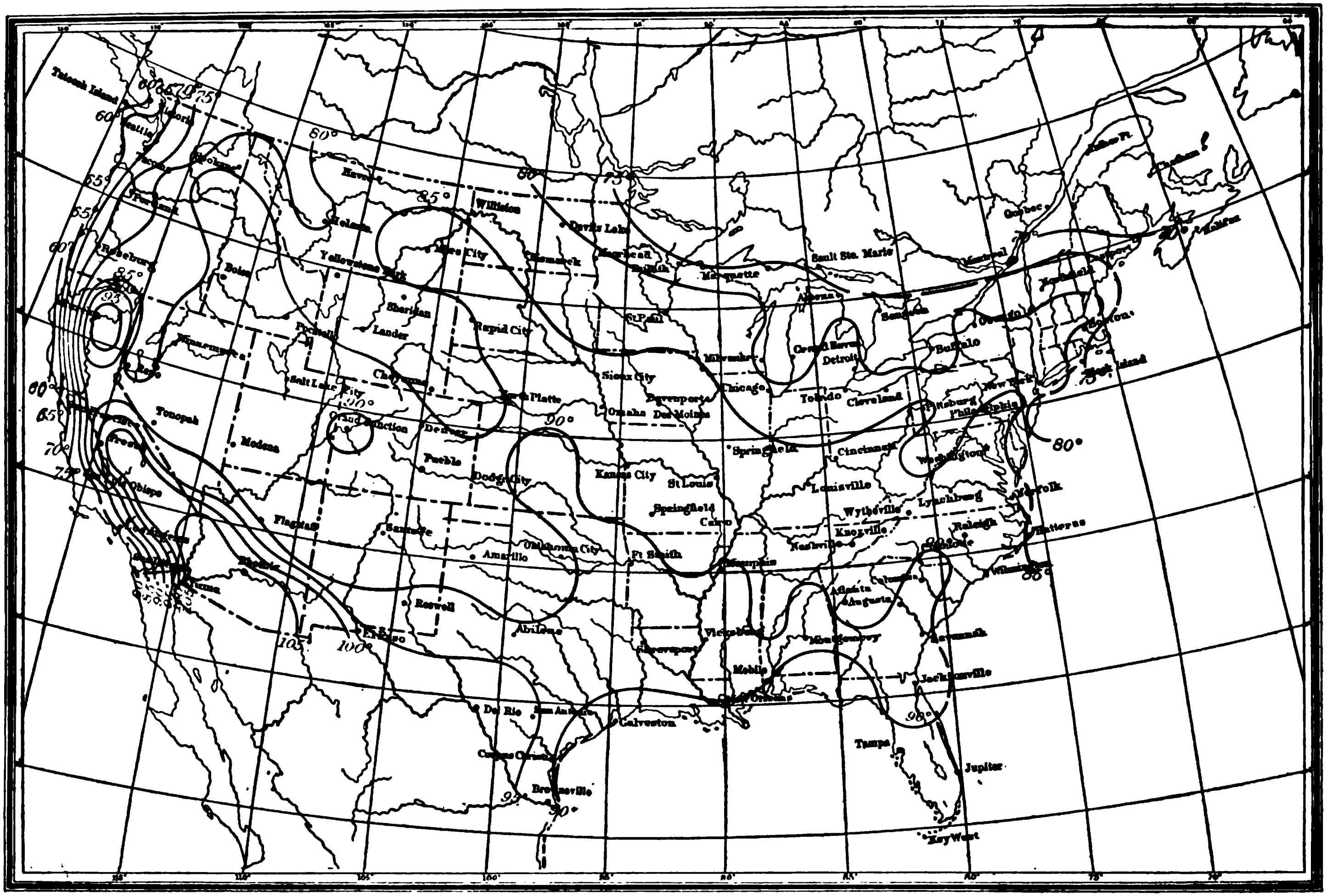

Chart 39.—Mean Maximum Temperature for July (Henry).

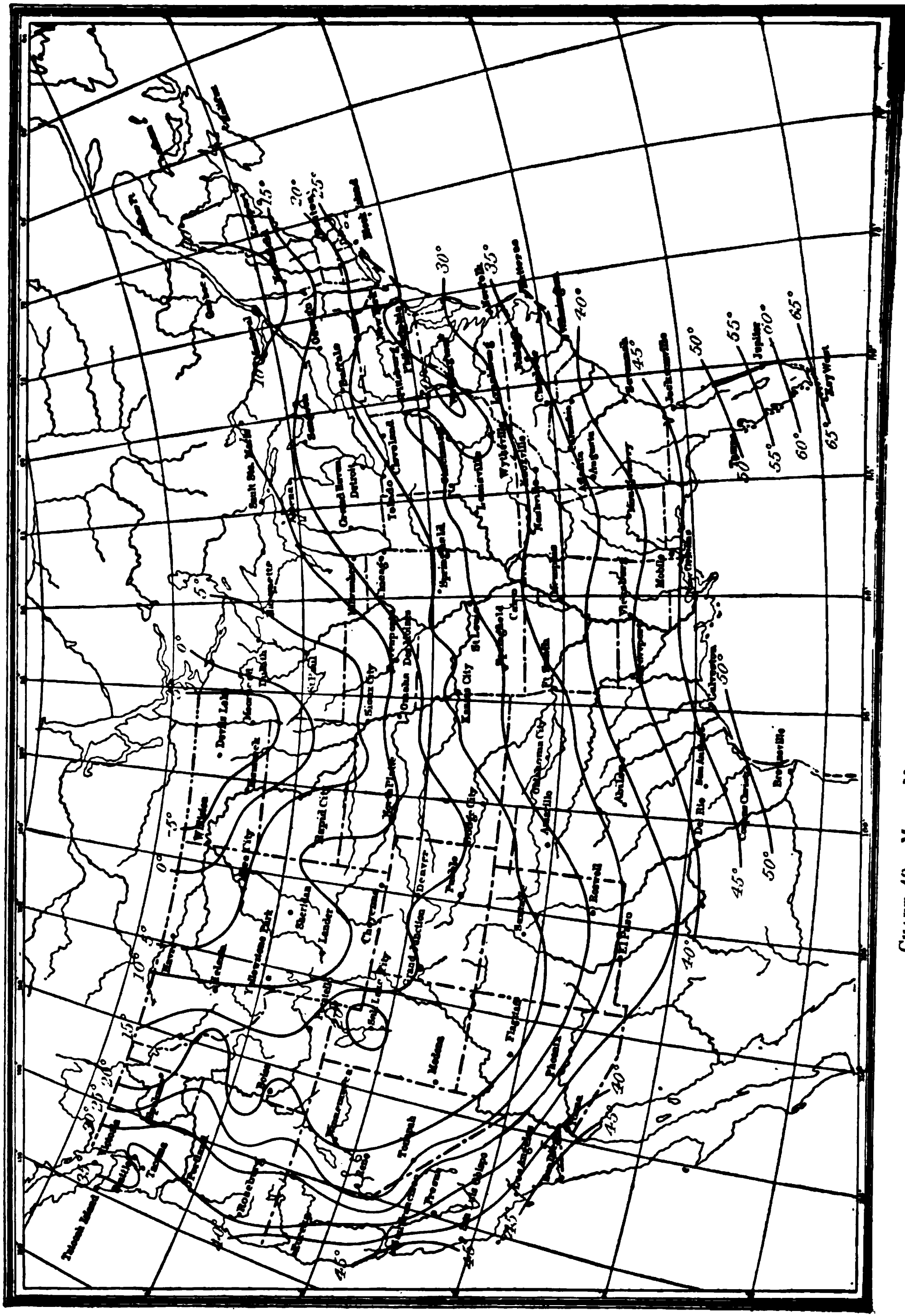

CHART 40.—MEAN MINIMUM TEMPERATURE FOR JANUARY (Henry).

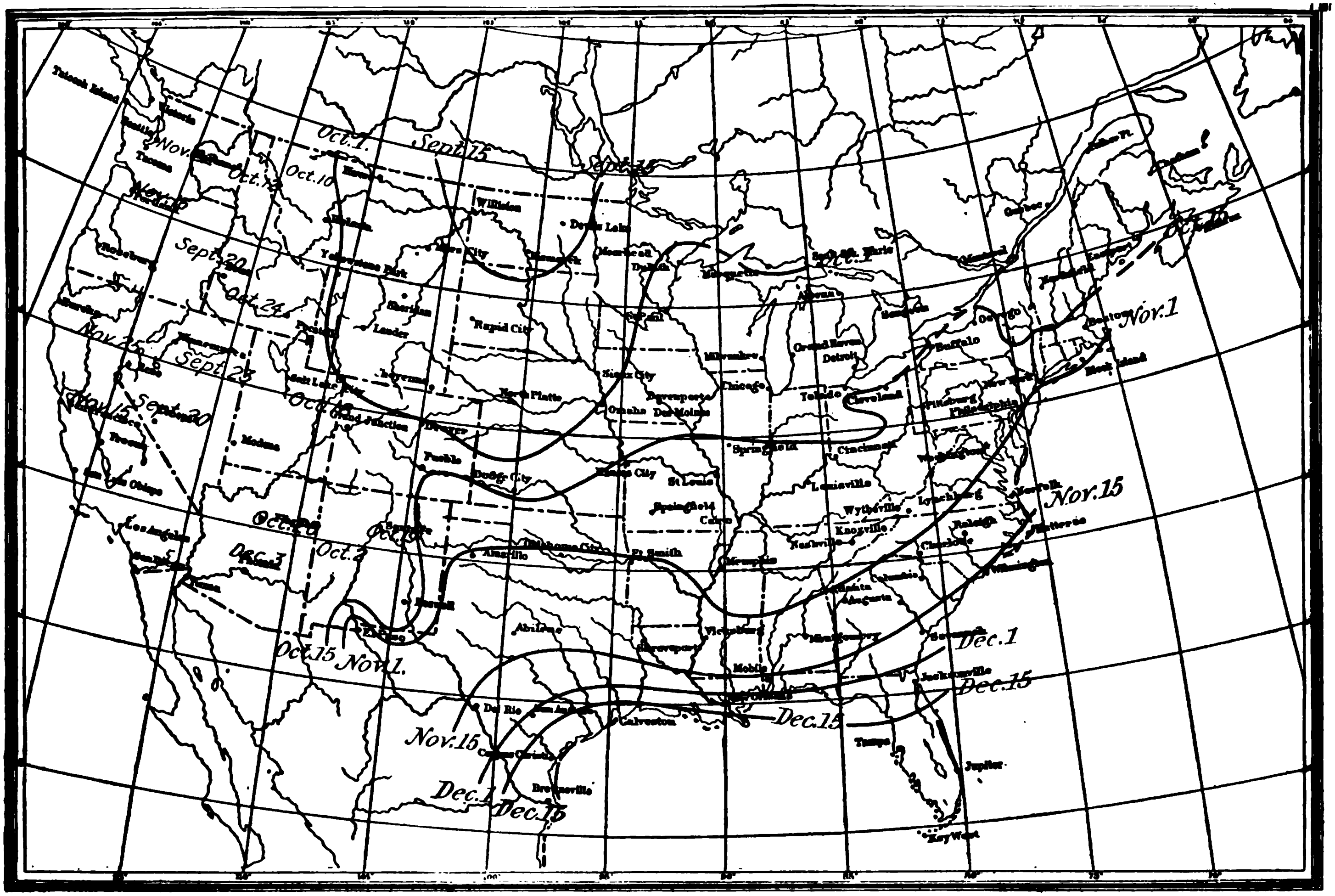

CHART 41.—AVERAGE DATE OF FIRST KILLING FROST IN AUTUMN (Henry).

It was not deemed advisable to attempt to draw lines of equal frost dates over the Mountain and Plateau region west of the 103d meridian, but the average dates for Weather Bureau stations in that region have been entered on the charts.

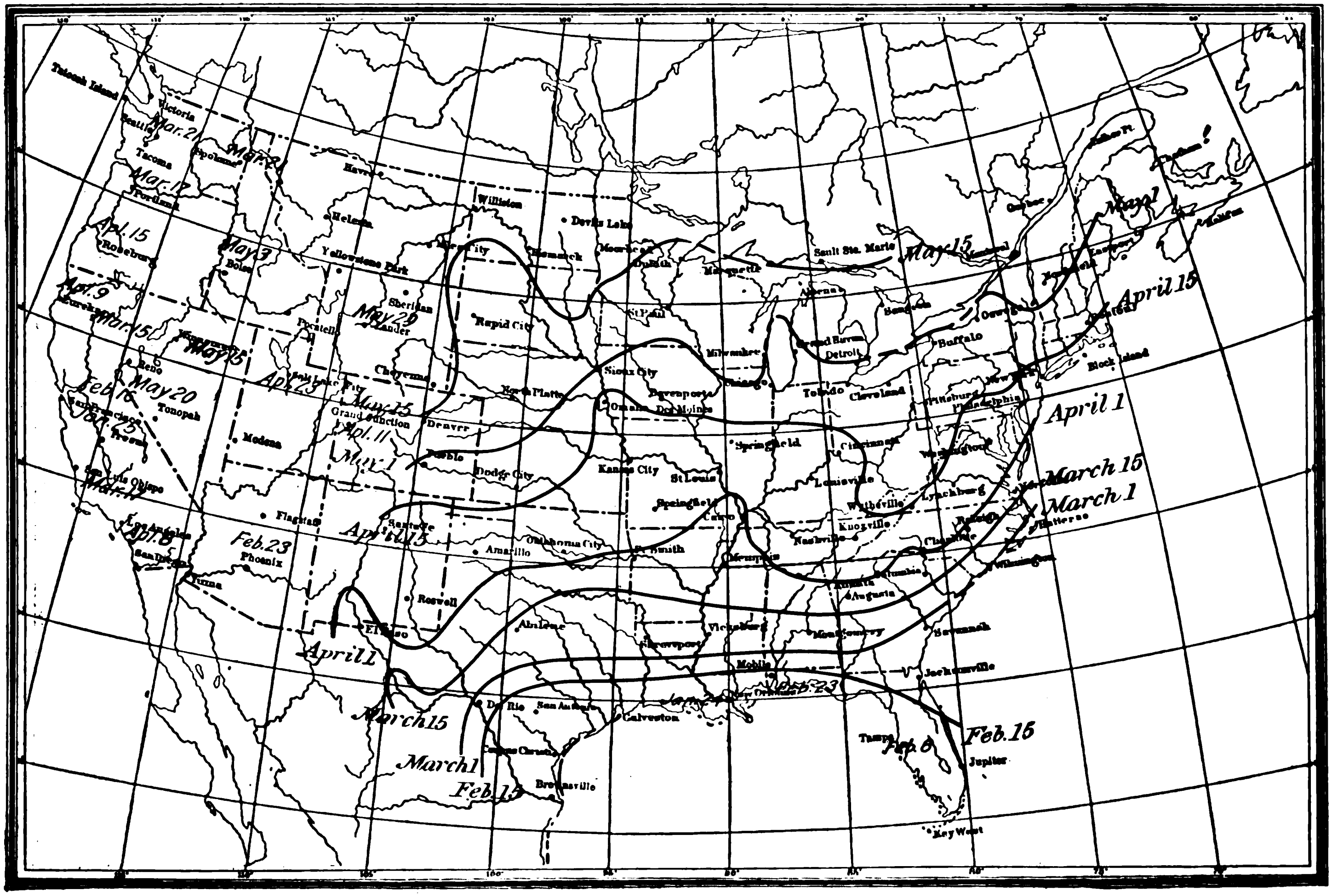

CHART 42.—AVERAGE DATE OF LAST KILLING FROST IN SPRING (Henry).

It was not deemed advisable to attempt to draw lines of equal frost dates over the Mountain and Plateau region west of the 103d meridian, but the average dates for Weather Bureau stations in that region have been entered on the charts.

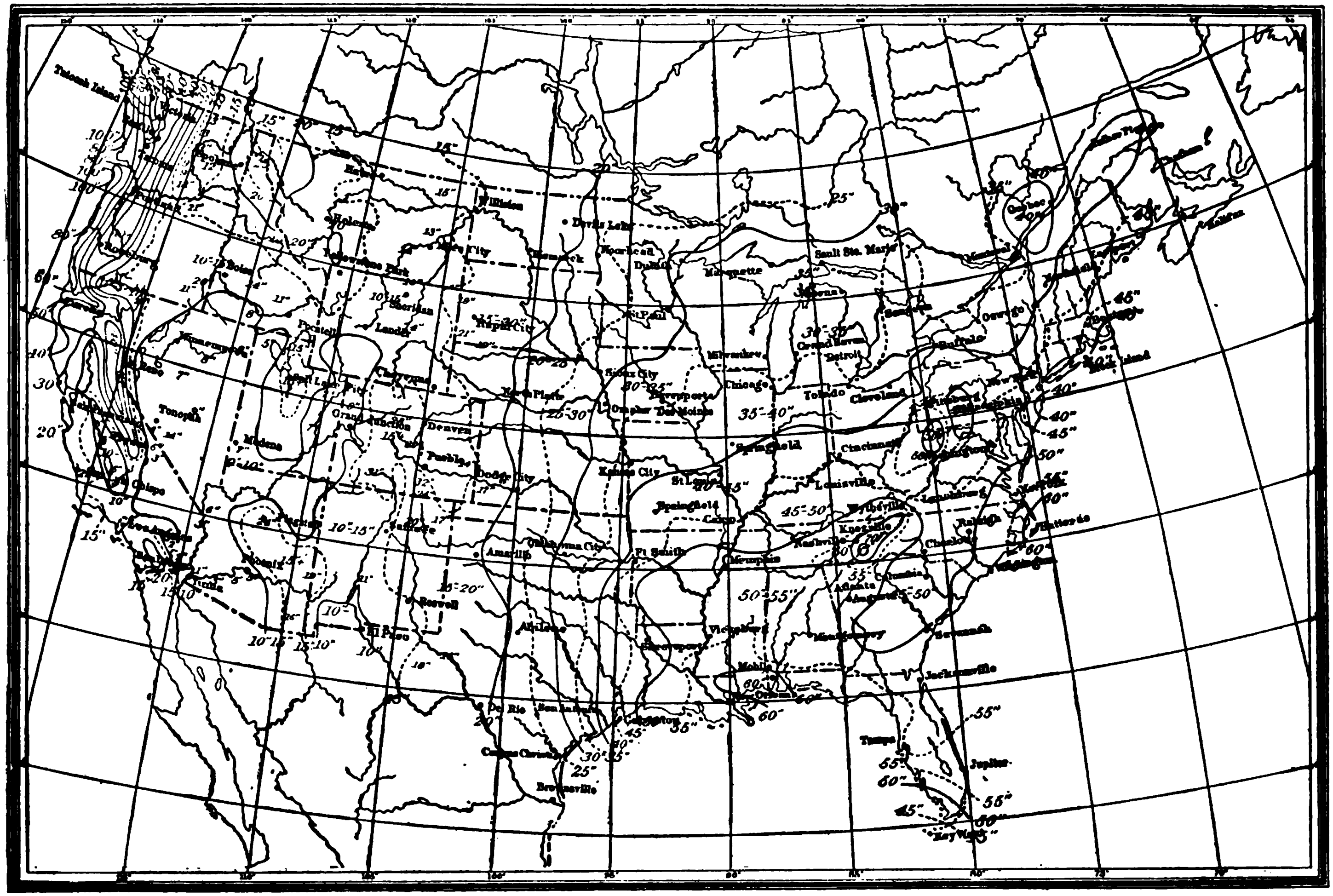

Chart 43.—Normal Annual Precipitation in the United States in Inches.

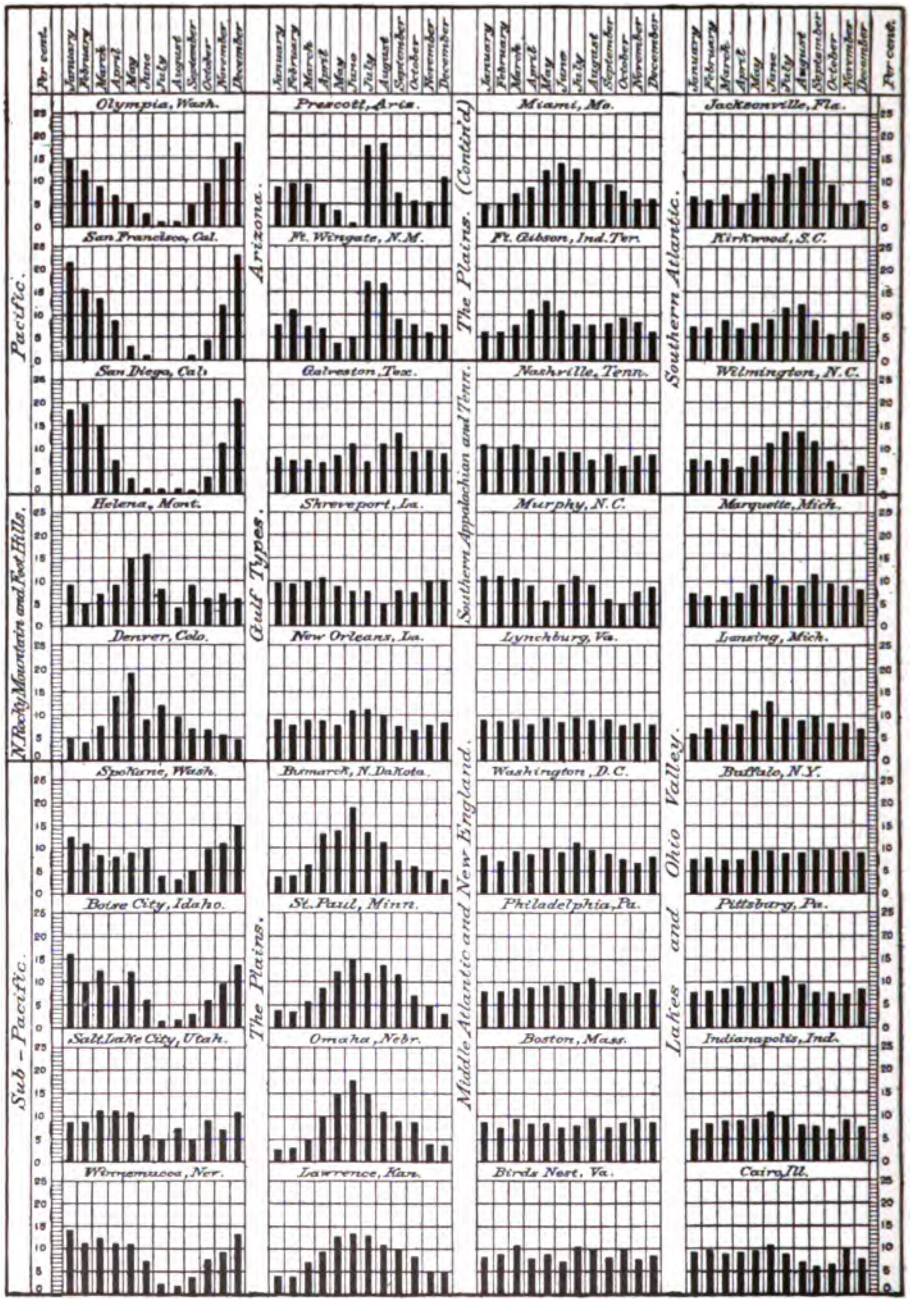

Chart 44.—Types of Monthly Distribution of Precipitation in the United States (Henry).

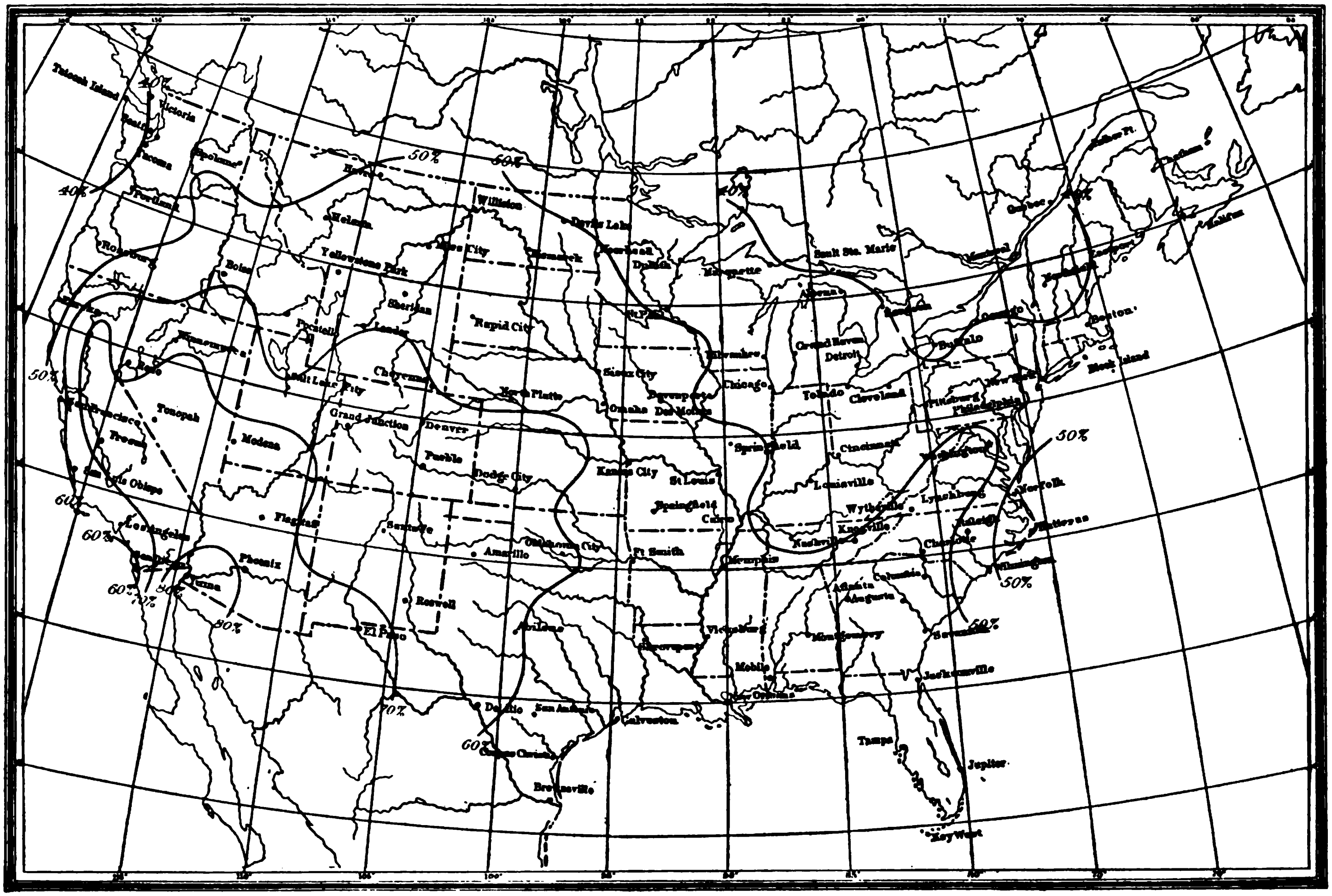

CHART 45.—NORMAL ANNUAL SUNSHINE IN THE UNITED STATES.

Percentage of possible. Compiled from all available observations at Weather Bureau stations from 1871 to 1894, inclusive.

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